PE

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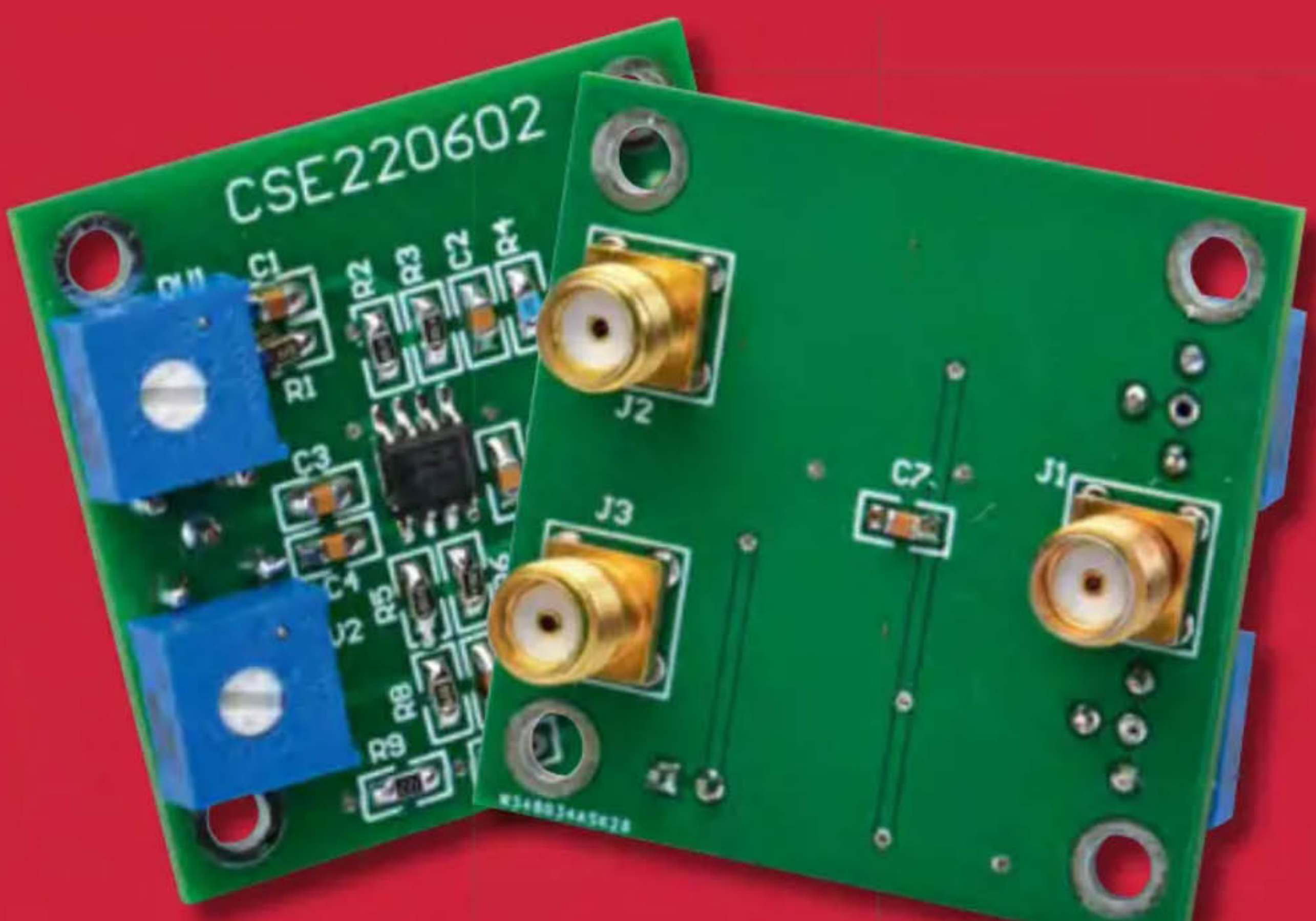
Topics in digital signal processing – sampling

Teach-In 2024
Analogue input and output with the ESP32 SoC microcontroller

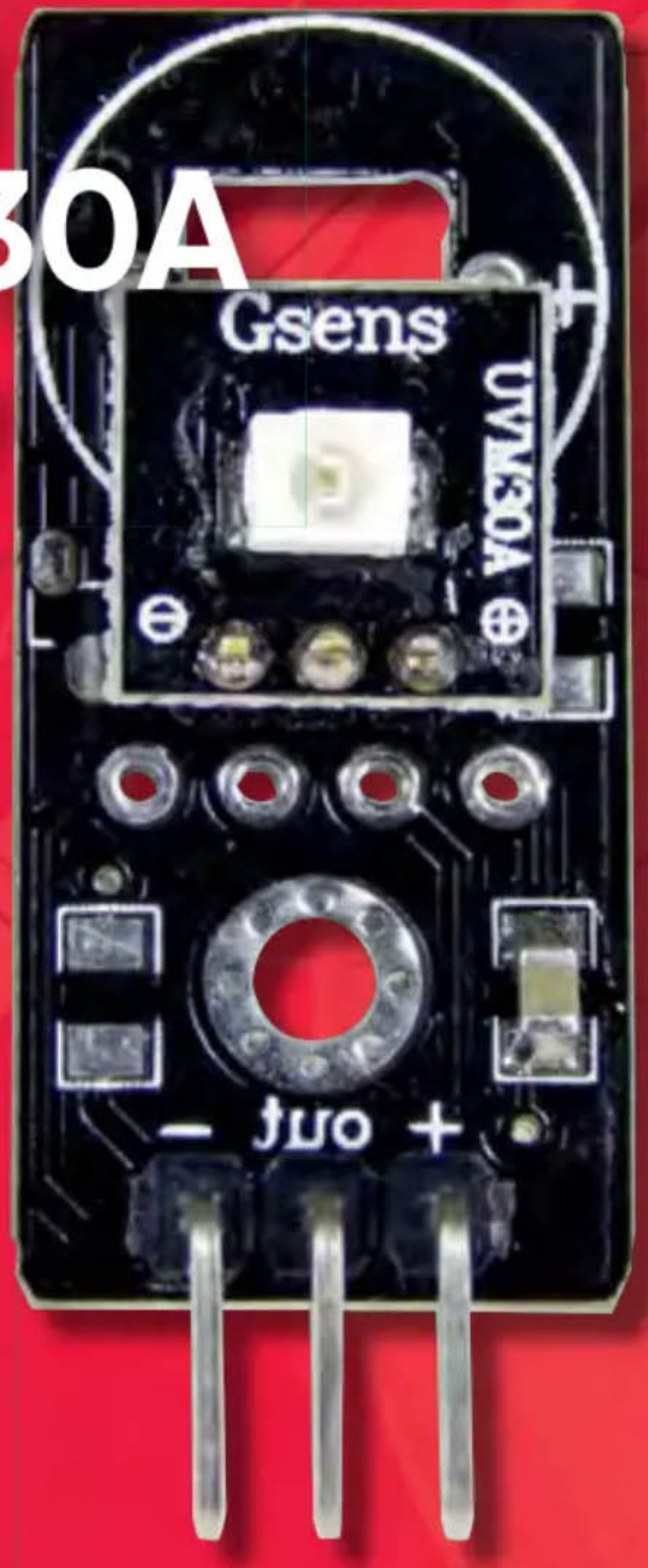
Audio Out
Designing discrete buffers

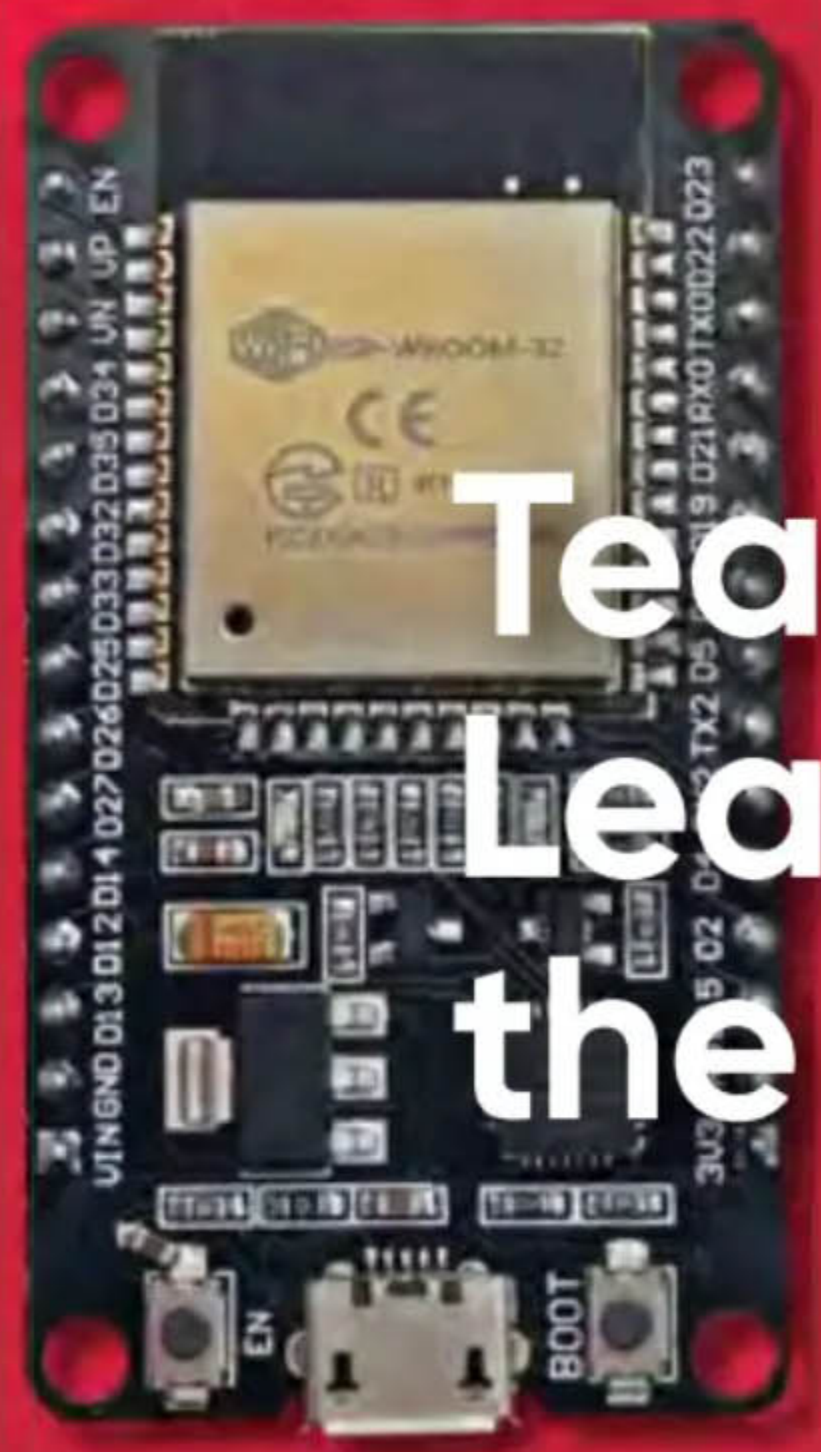
GPS-Disciplined Oscillator



Dual RF Amplifier

Mastering the UVM-30A UV Sensor





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Songbird: an ideal beginner's project

PLUS!

Techno Talk – One step closer to a dystopian abyss?
Cool Beans – Arduino: 7-segment display delights
Net Work – Electric cars, Moon-shot missions and more

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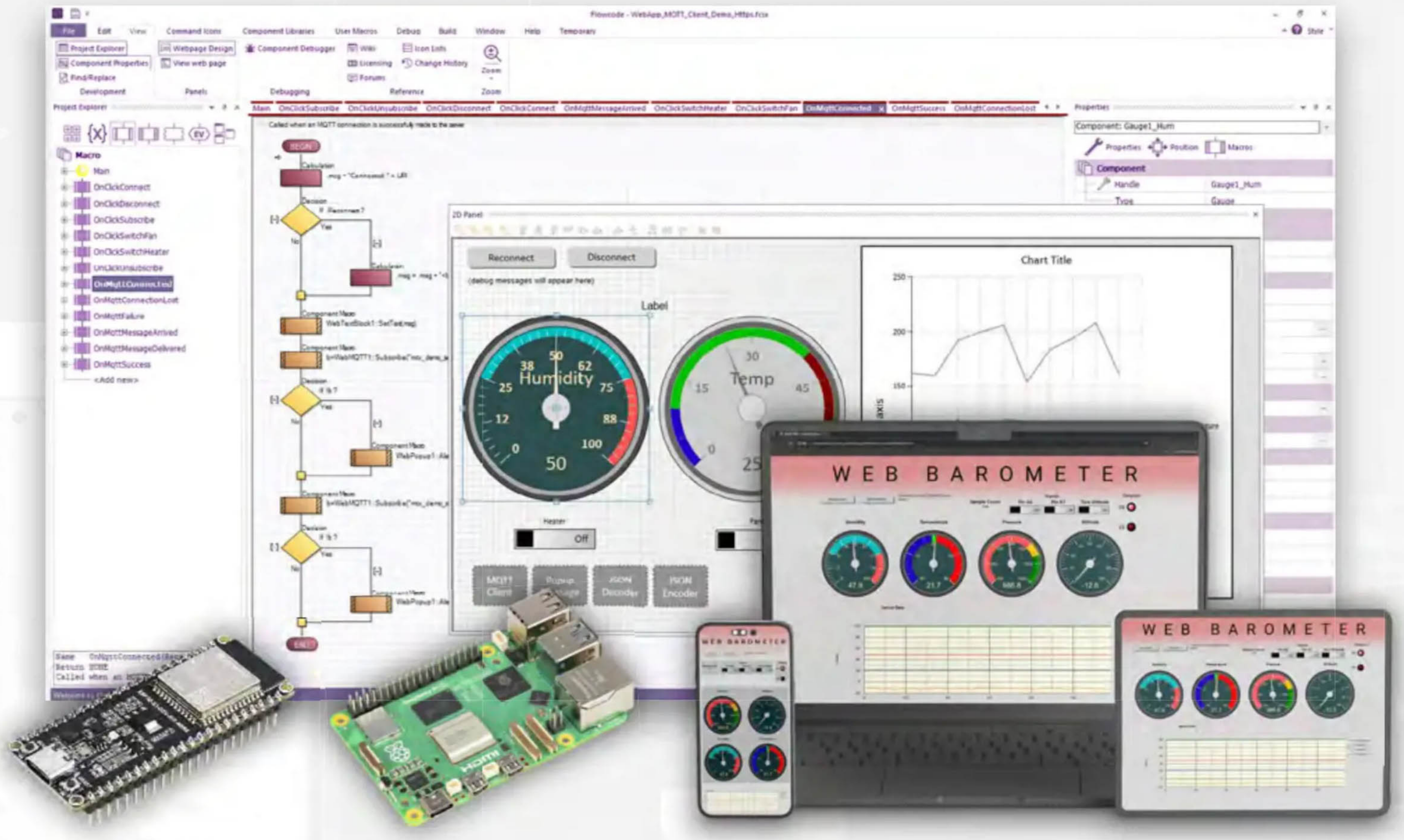
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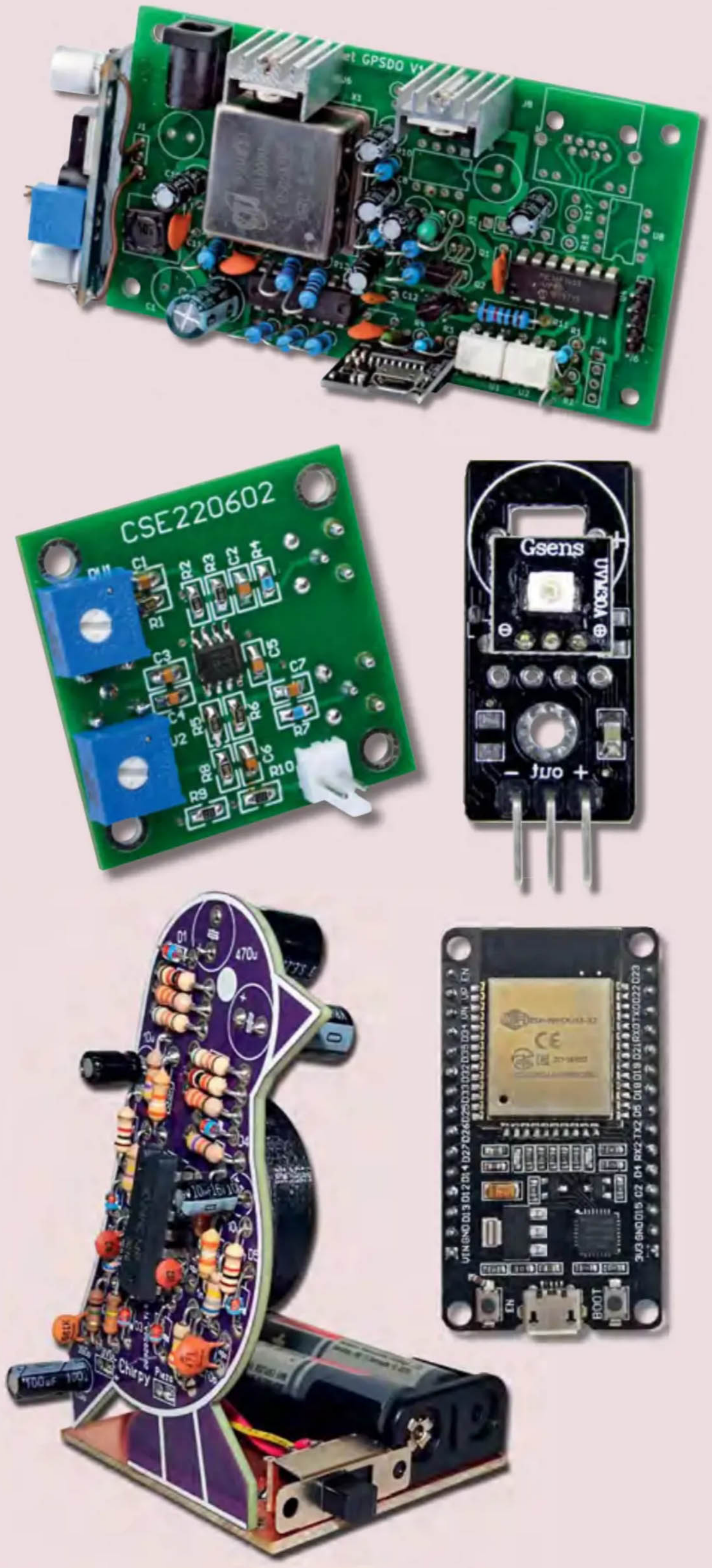

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The June 2024 issue of *Practical Electronics* will be published on Thursday, 2 May 2024 – see page 72.

Projects and Circuits

GPS-Disciplined Oscillator by Alan Cashin 16
This GPS-Disciplined Oscillator is mostly built in software, so it only requires a PIC, an oven-conditioned crystal oscillator and a few other supporting parts. It provides an extremely accurate 10MHz signal with an error in the parts per billion range.

Dual RF Amplifier by Charles Kosina 26
This small RF amplifier has two outputs with individually selectable gains. This makes it suitable to add to a signal generator to provide a higher output level, or for better drive strength, or 'fanning it out' to multiple other pieces of equipment and more.

UVM-30A Module Ultraviolet Light Sensor by Jim Rowe 29
This UV light-sensing 'breakout' module detects the intensity of UV solar radiation and hence the degree of protection you may need to prevent skin damage. If you connect it to an Arduino or other microcontroller, it can even indicate the current 'UV Index'.

Songbird by Andrew Woodfield 33
Here's a decades-old design brought up to date in a new package and made to appeal to beginners as well as experienced builders. It's quick and easy to build and a great project if you're new to electronics.

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Reports on an environment monitor and Tapo smart sensors; news of forthcoming (expensive!) electric cars from Lotus; plus a roundup of current Moon-shot missions.

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WIRELESS FOR THE WARRIOR

by **LOUIS MEULSTEE**

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

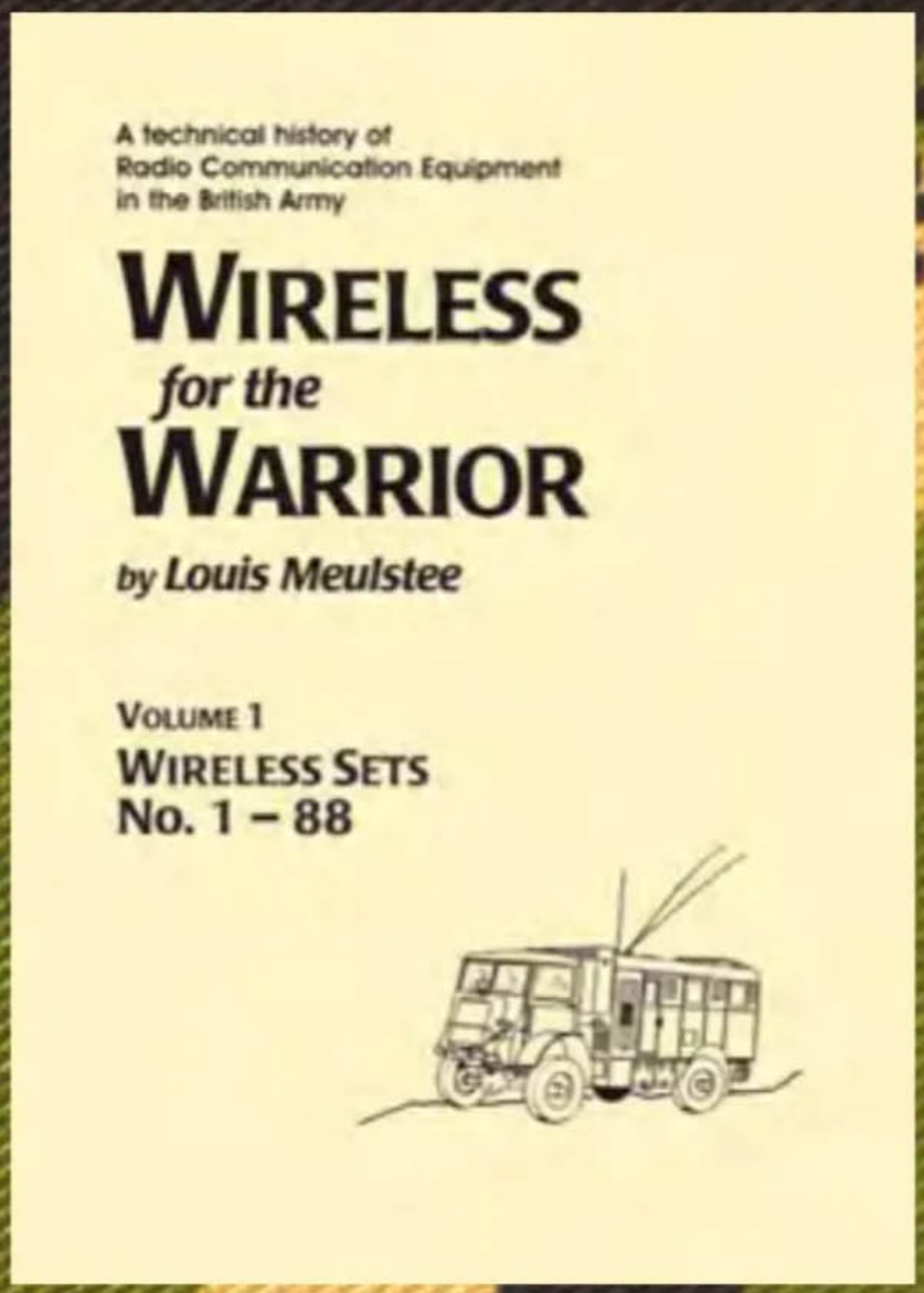
The *Wireless for the Warrior* **books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.**

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 **and** *Volume 2* **cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.**

Volume 3 **covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.**

Volume 4 **covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.**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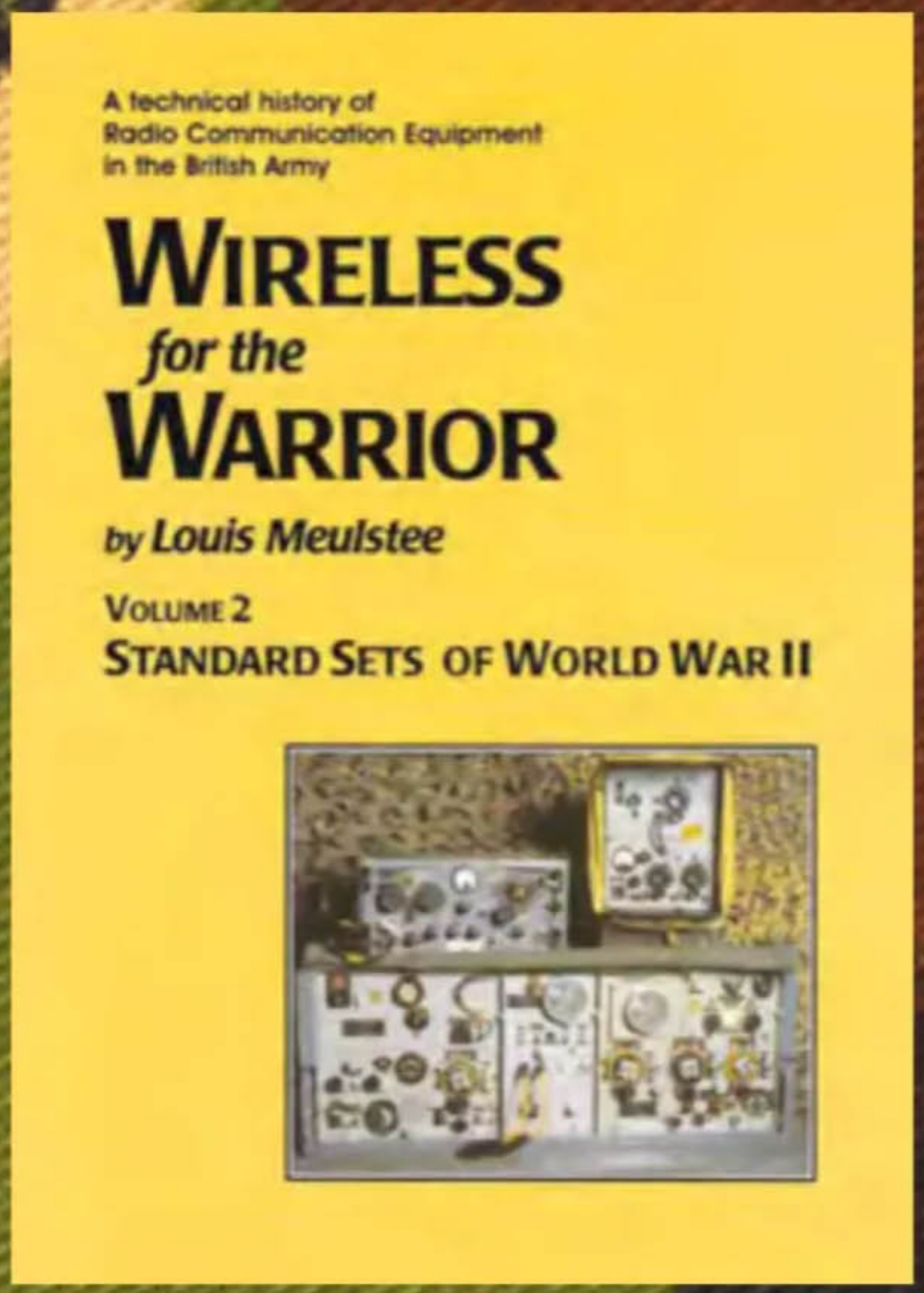
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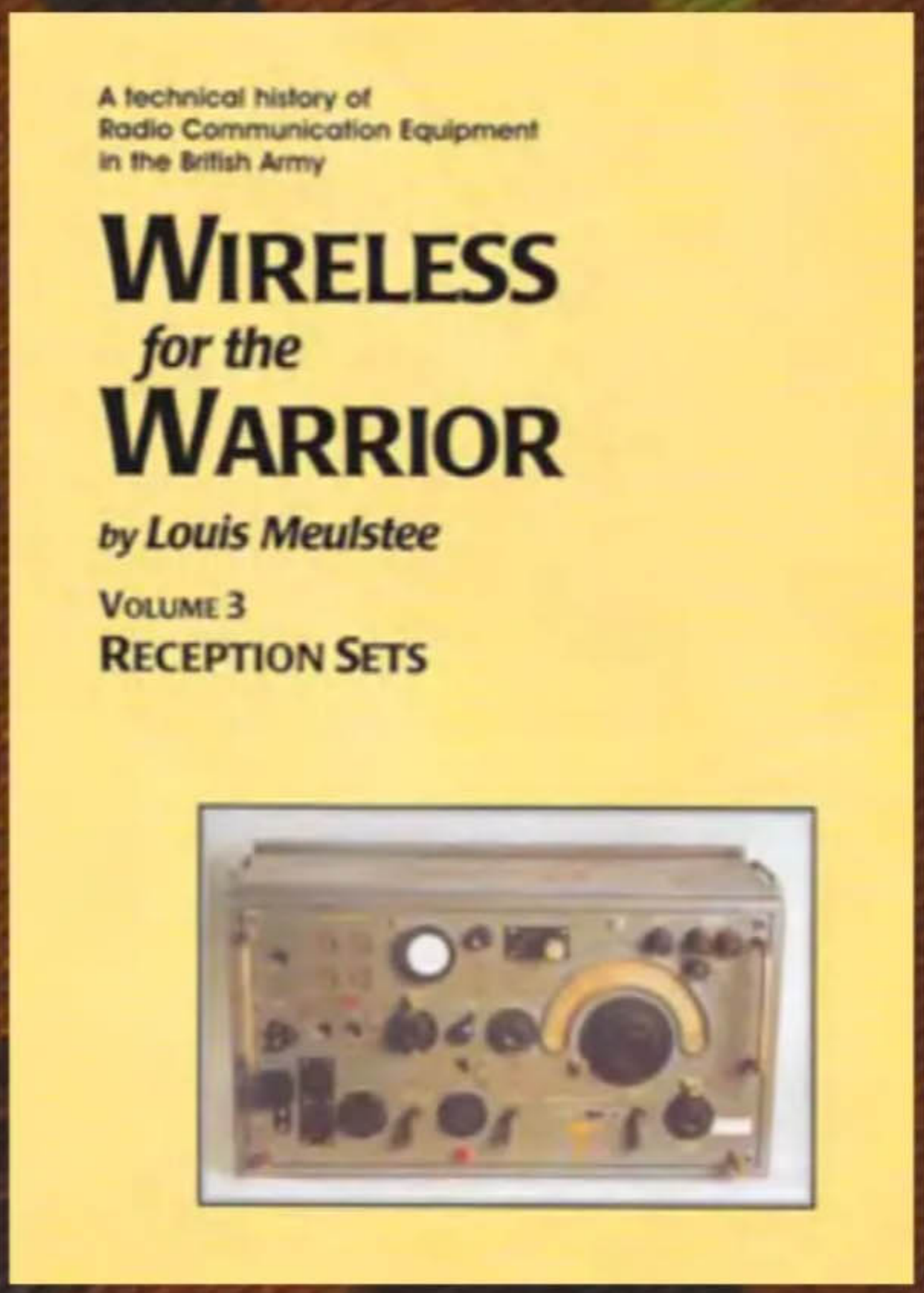
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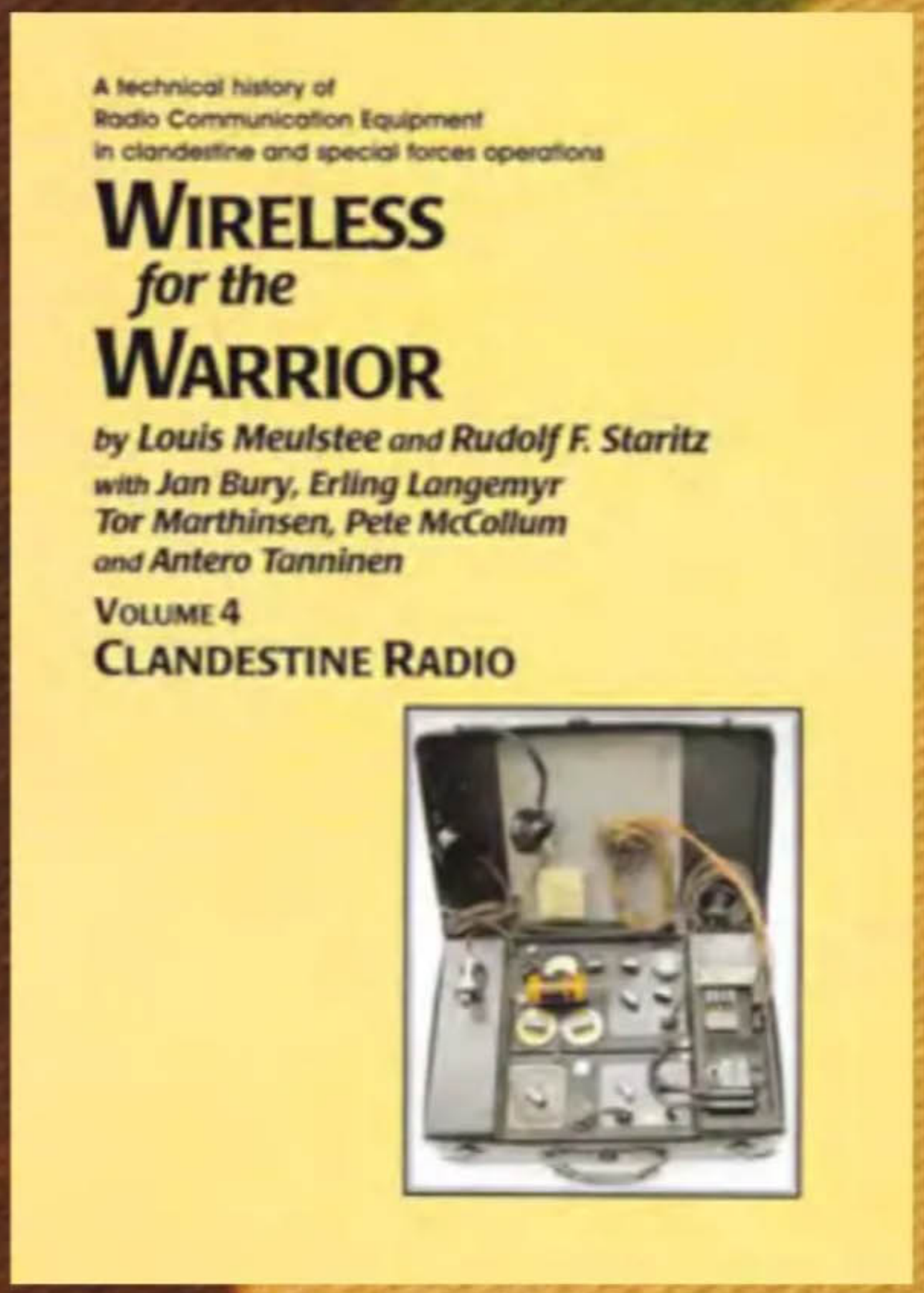
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*Order Code: KSR17 - **£29.95.***

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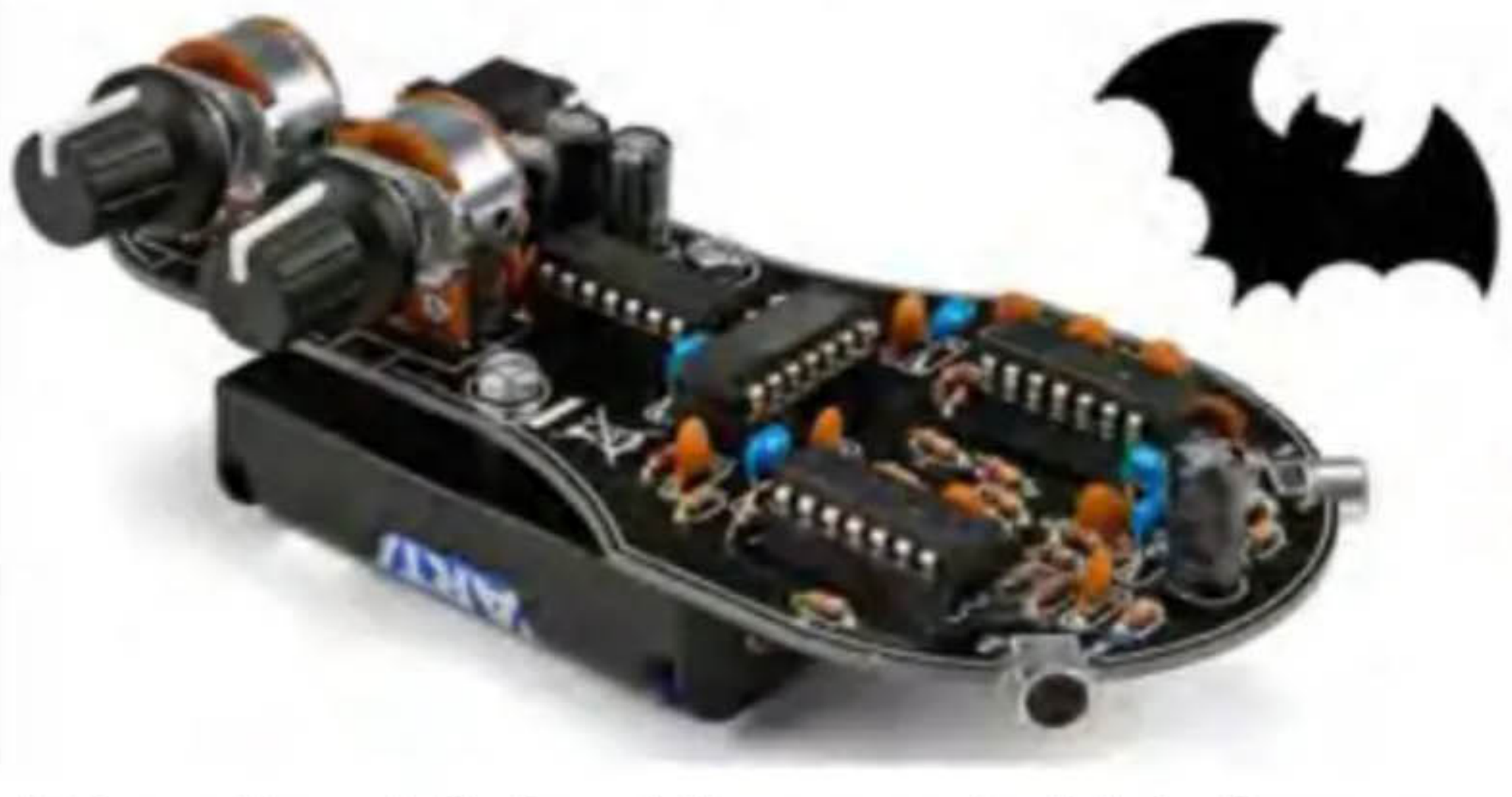
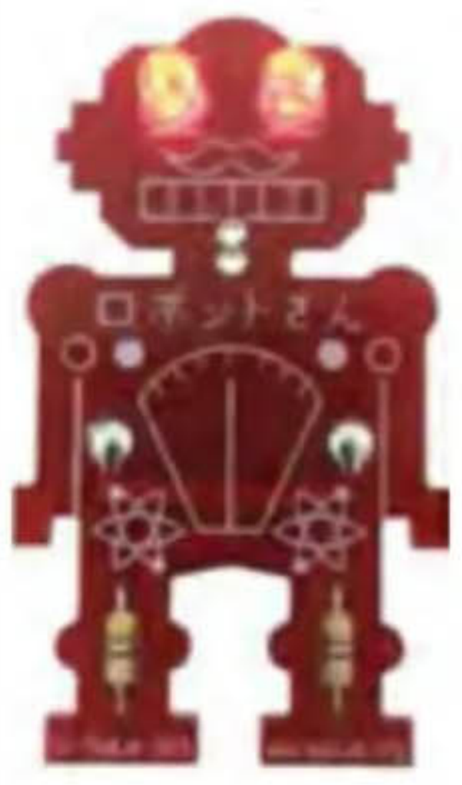


Educational & fun kit converts high frequency sounds (20 - 90kHz) normally imperceptible to humans like bat signals into audible noise. Can also help detect failures in machines, engines, etc. Stereo feature adds the possibility to pinpoint the source. Frequency range 20-90kHz. 3.5mm jack output. 129x60x40mm. Requires 3x AA batteries and stereo headphones (not included).
*Order Code: WSAK8118 - **£20.39***

NEW! Mr Robot Kit



A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
Order Code: WSL108 - 6.68

LED Electronic Dice Kit

Still popular! A must-build soldering kit for all beginners. Dice slowly rolls to stop on a random number when the push button is released. 9V battery (not included). Ideal for educational courses. Wide selection of component types.
*Order Code: MK109 - **£7.08***

3 Channel RGB LED Light Organ Kit

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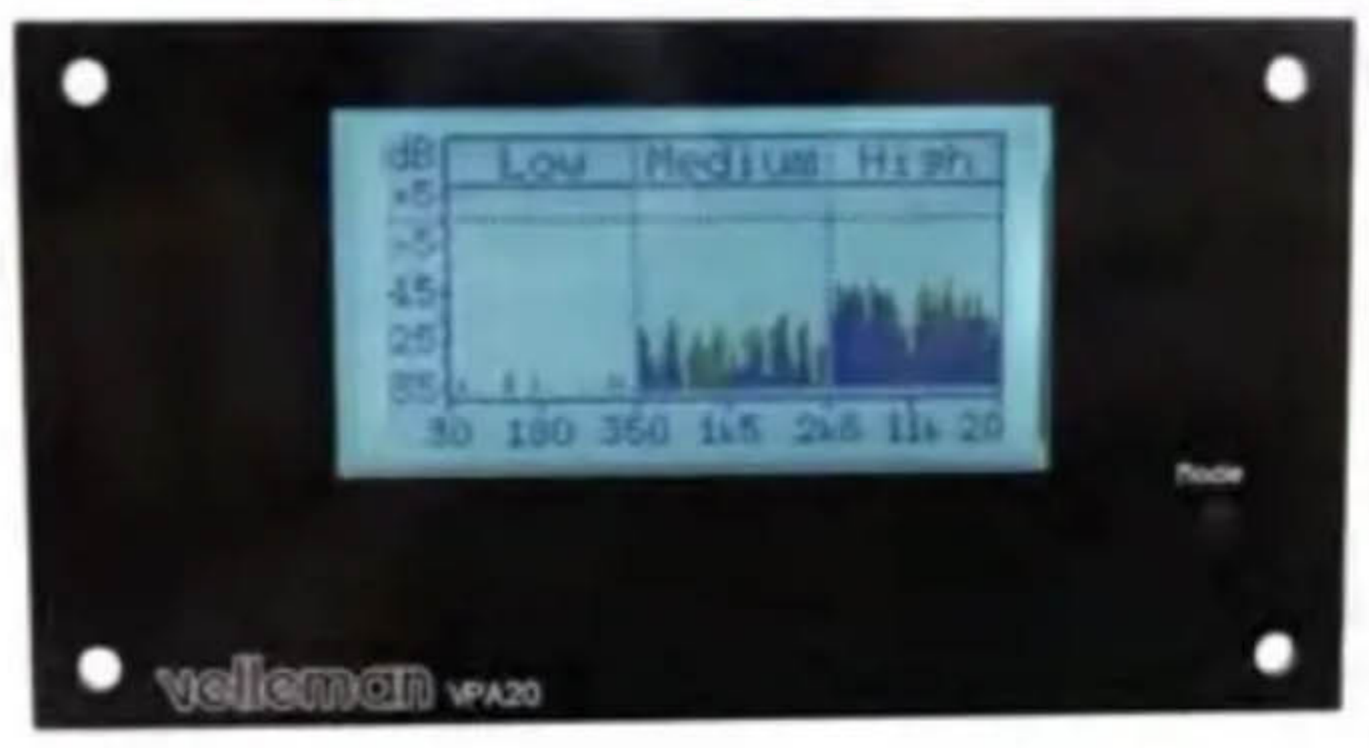

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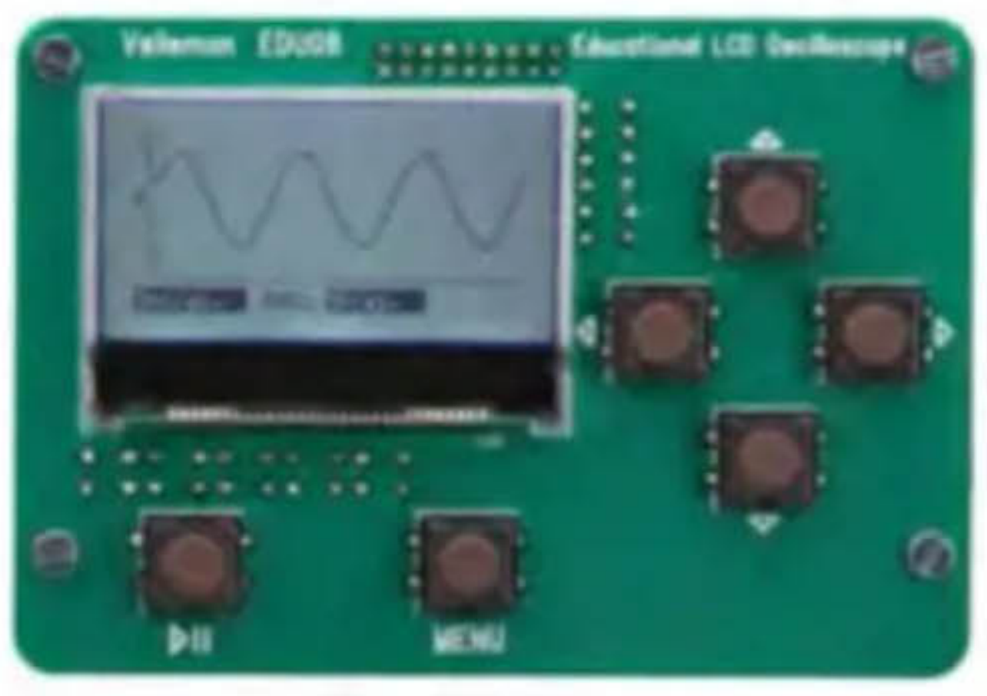

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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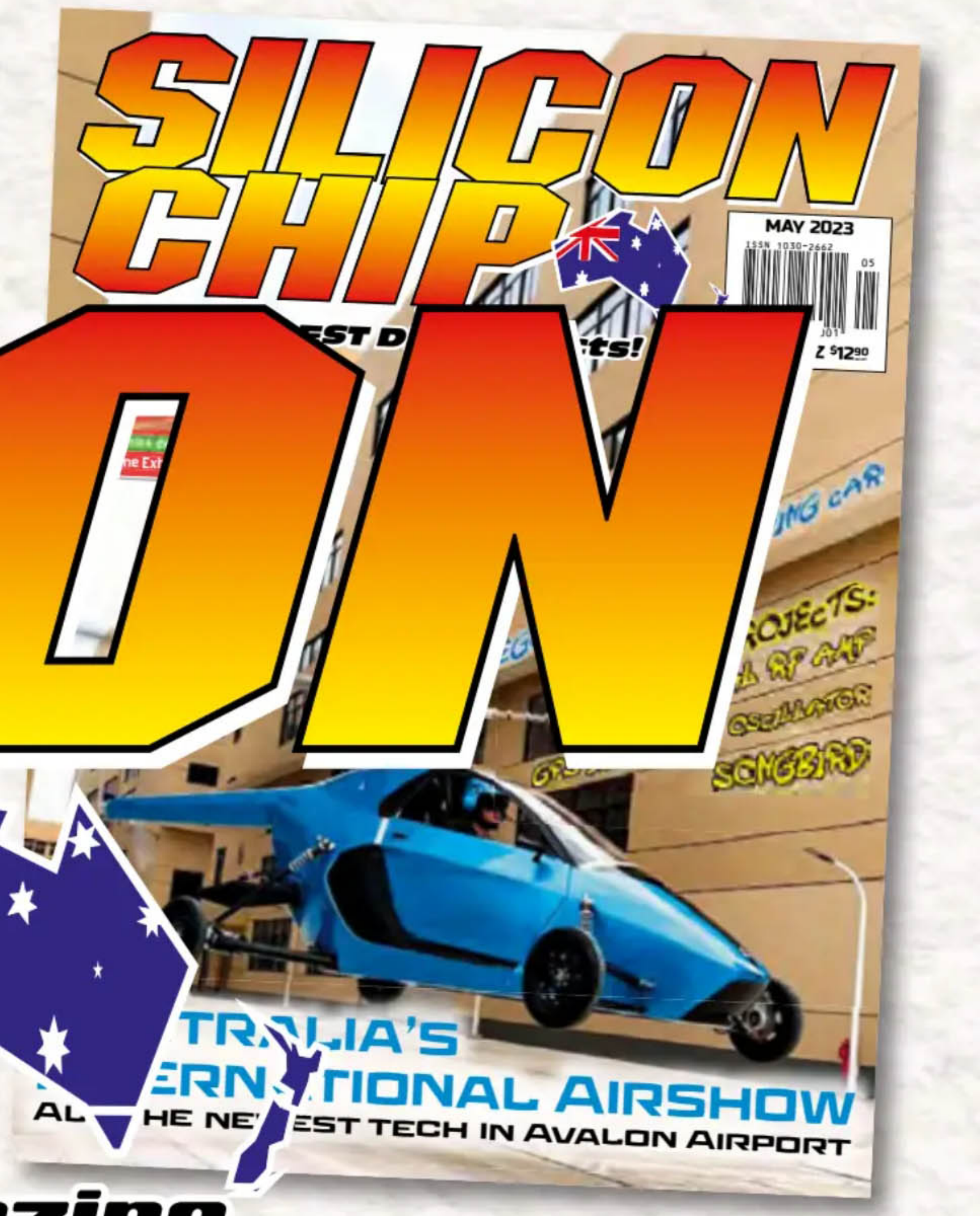
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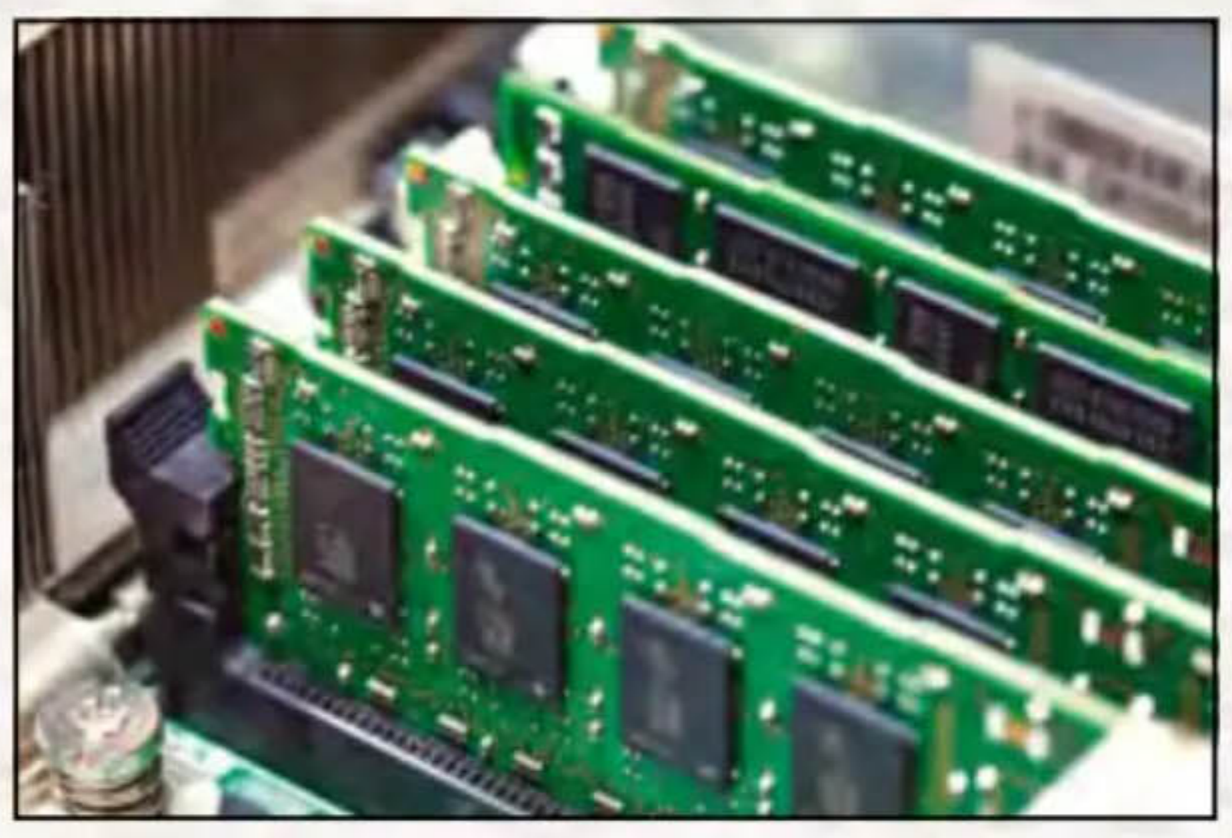

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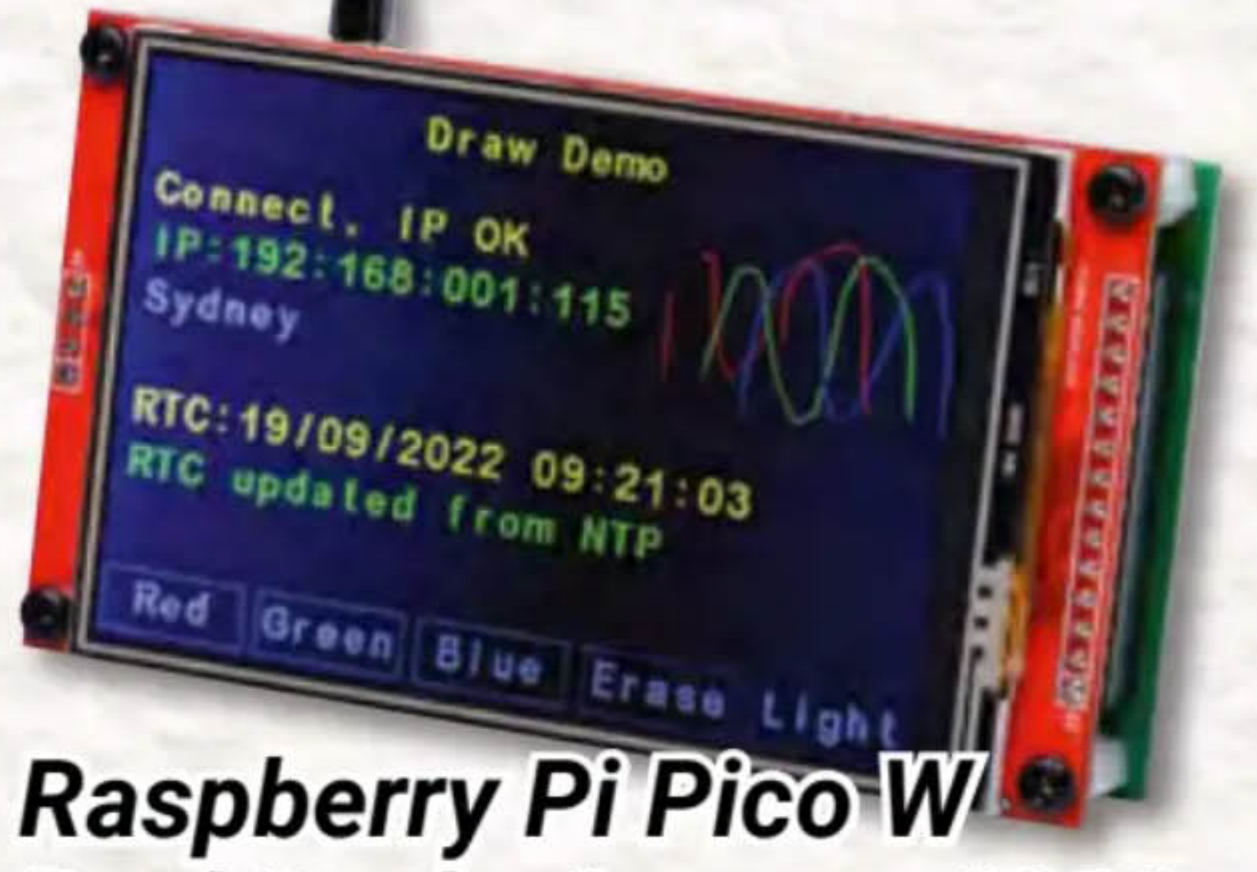
Draw Demo
Connect. IP OK
IP:192:168:001:115
Sydney
RTC:19/09/2022 09:21:03
RTC updated from NTP
Red
Green
Blue
Erase
Light

Raspberry Pi Pico W BackPack; January 2023

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Welcome to May!

'Spring is sprung,' well nearly, and what better way to welcome in the new season than with a little inspiration from a *Songbird* – in this case an electronic one. This month's avian project is just one of four to keep you busy with a soldering iron. Our silicon-based warbler is an ideal beginner's circuit. It contains no SMDs or tricky construction techniques, and a very pleasing result can be obtained in just a few hours of productive work. It would be ideal for a youngster who wants to build their first electronic project, ideally under supervision from someone with experience of using the necessary tools.

For those of you with more experience, the *Dual RF Amplifier* and *GPS-Disciplined Oscillator* (*GPSDO*) provide very useful testbench circuits that you will likely use again and again.

Last, but not least, we welcome the return of Jim Rowe's excellent overviews of cheap sensors and modules. This month, he provides a handy explanation of a low-cost UV sensor module. Jim is based in famously sunny Australia, so perhaps the more cynical among you may well wonder why we should worry about UV in the famously less sunny (cloudy) UK. Well, I checked with the UK's Met Office and UV can certainly be a problem in Britain, especially for those with fairer skins, so I think it is well worth learning to use this module – wherever you are based!

Topics in Digital Signal Processing

All of this month's columns are excellent, but perhaps the one I am most excited about is the start of a new series by Ian Bell in *Circuit Surgery*. Ian will be examining topics in a notoriously tricky (mathematically heavy) subject – digital signal processing, or DSP for short. We work hard at *PE* to avoid mathematics in our coverage of electronics and Ian will do the same with DSP. There may be a little 'toe dipping' into mathematics, but by and large his explanations will give insight into a very important electronics subject without the intimidating algebra. Who knows, perhaps his column will inspire you to go off and do your own research, adding as much mathematics as you are comfortable with. I know that will certainly be my approach.

Matt Pulzer
Publisher

One step closer to a dystopian abyss?

Techno Talk

Max the Magnificent

As always, we live in exciting times. Indeed, times are getting more exciting by the minute. Can you imagine being able to simply look at something, ask a question, and receive a spoken answer from an AI? I just saw such a system in action!

In my previous column (PE, April 2024), we talked about the concept of mixed reality (MR), which encompasses augmented reality (AR), diminished reality (DR), virtual reality (VR) and augmented virtuality (AV).

Mixed reality is exciting, but the real game-changer will come when we combine it with artificial intelligence (AI), all boosted by the awesome data bandwidths promised by mmWave 5G and 6G cellular communications. The question is, whether this will be a game-changer for good… or the other sort.

Where are we?

A large language model (LLM) is an AI model notable for its ability to achieve general-purpose language understanding and generation. The first LLM to impinge on the general public's collective consciousness was ChatGPT. Created by OpenAI, ChatGPT began to roam wild and free in November 2022, which is only around 18 months ago as I pen these words.

This form of Generative AI (GenAI) is now all around us. There are AI-based writing tools (give them a few text prompts and they will write your marketing slogans, product descriptions, brochures… and so on); AI-based presentation-generation tools (give them a few text prompts and they will generate your PowerPoint presentation for you); AI-based speech-to-text transcribers (give them an audio or video file and they will return the written transcript); AI-based content summarisers (give them an audio or video file – or the output from a transcriber – and they will return a summary along with a list of action items); text-to-image generators (I'm currently having a lot of fun with Stable Fusion), and – most recently – a company called DeepMotion announced a text-to-3D-animation tool called SayMotion.

In my case, I'm particularly interested in how AI might help with hardware design and software development. As a case in point, shortly before I started to write this column, I whipped up a tiny test program to run on an Arduino Uno. This comprised only 34 lines of code, 20 of which were items like { and }. Out of the 14 lines containing more meaty statements, 11 of them (that's close to 80%) had bugs, and this was one of my better days!

Prior to the introduction of LLM-based assistants called copilots, embedded software developers typically spent 20% of their time thinking about the code they were poised to write, 30% of their time writing the code they'd just thought about, and 50% of their time debugging the code they'd just written. By comparison, 60% of today's embedded code is automatically generated by GitHub Copilot. This would offer a tremendous performance boost if not for the fact that – since Copilot was trained on open-source sources – 40% of the code it generates has bugs or security vulnerabilities. Fortunately, we have Metabob from Metabob (don't ask), which is a form of copilot that identifies and addresses any problems introduced by humans and other AIs.

Where are we heading?

There's a famous quote: 'It is difficult to make predictions, especially about the future.' This quote is so famous that no one knows who said it. It's been attributed to all sorts of people, from Mark Twain to Niels Bohr to Yogi Berra. Whoever did say this knew what they were talking about. I would never have predicted many of the technologies we enjoy today. Contrariwise, some of the technologies I was looking forward to seeing have failed to materialise (in more ways than one).

One of the questions I often ask technologists when I'm interviewing them is, 'Will we have technology XYZ next year?' (where XYZ is whatever futuristic technology forms the topic of our conversation). Of course, they always answer 'No.' My next question is, 'Will we have this technology in 100 years' time?' To this, they always respond 'Yes.' Then I say: 'So, now we have the endpoints, all we need to do is narrow things down a little.'

I am confident it won't be long before we are all sporting some form of MR 'something or other.' Personally, I think one of the MR interfaces intended for daily usage that will arrive on the scene sooner rather than later will look a bit like a pair of ski goggles, but I'm prepared to be surprised by something else.

When people tell me that they would have little use for an AI+MR solution, I think back to the early 2000s when the same folks told me they had no use for phones that could take pictures ('All I want to do with my phone is make calls'). All I can say is, 'Look at you now!'

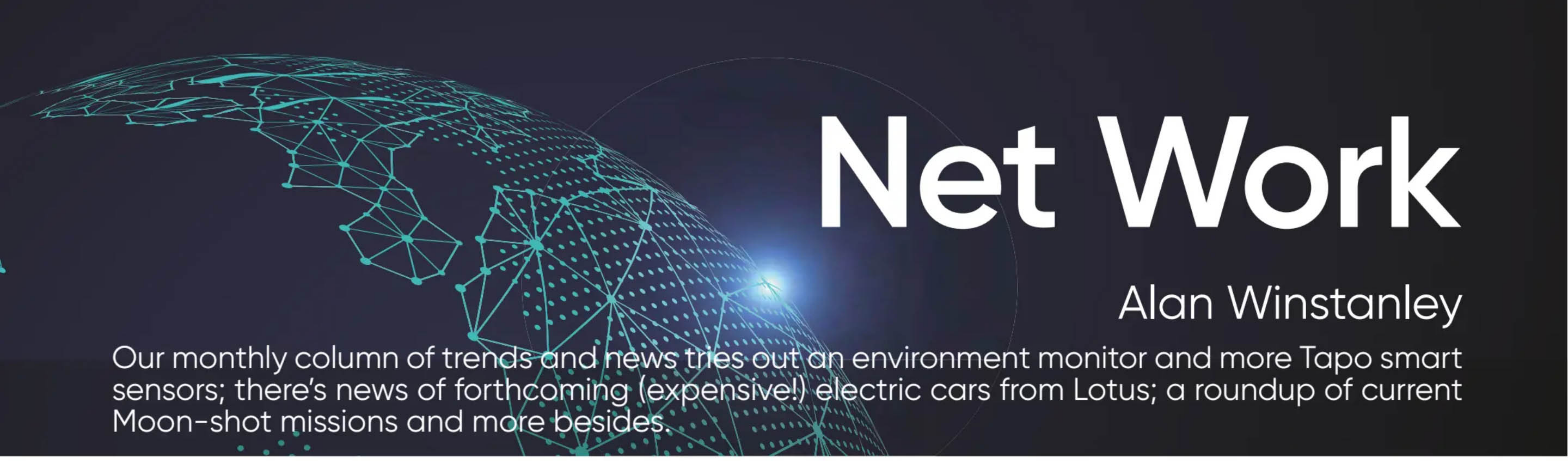
One of the examples I often present is being able to ask my AI+MR combo a question like, 'What was that book I was reading a few months ago that talked about AI and Ada Lovelace?' I can envisage the AI responding with the name of the book, while the MR highlights its location on my bookshelf.

There are several required 'building blocks' that are starting to fall into place. For example, a company called Prophesee makes a teeny tiny event-based vision sensor that's only 3mm x 4mm in size and consumes only 3mW of power. Another company called Zinn Labs has mounted these sensors in a pair of glasses frames that are also equipped with an eight-megapixel forward-looking camera, microphones, loudspeakers, and a cellular connection to a cloud-based AI. The camera captures the scene while the sensors track what your eyes are looking at.

I've seen a demo where the user looks at something like a plant and simply asks a question like, 'Can I grow this plant indoors?' The AI immediately responds, 'Yes, but it requires bright light, so you'll need to place it near a south-facing window.'

Horns and swords

I feel like we are sitting on the horns of a dilemma with a Sword of Damocles hanging over our heads (I never metaphor I didn't like). I hope we're heading toward an age of wonder; I fear we're one step closer to a dystopian abyss. Pass me my dried frog pills.



Net Work

Alan Winstanley

Our monthly column of trends and news tries out an environment monitor and more Tapo smart sensors; there's news of forthcoming (expensive!) electric cars from Lotus; a roundup of current Moon-shot missions and more besides.

Last month, the author tried out the Chinese online vendor Temu for the first time, after finally succumbing to an introductory offer of a heavily discounted Bluetooth thermal label printer. Initial impressions of the service were encouraging, and it wasn't too long before more Temu orders were on the way.

It must be said that Temu's website impresses in many respects, and clearly Temu has gone to some lengths to reassure consumers and remove any nagging doubts and uncertainty that potential buyers might have about sourcing goods directly from China. A myriad of merchandise is on sale and website users will see a slick shopping cart and seamless integration with credit card processing, highlighting an emphasis on PCI DSS (Payment Card Industry Data Security Standard) compliance –Western-standard data protection conditions that vendors must follow when handling credit and debit card details. Options to cancel orders, or add to existing ones before despatch, are also offered provided you're quick enough. Everyone hates buying something only to see the price drop soon afterwards, so Temu's 'Price Adjustment' policy promises to refund the difference within 30 days. In Britain, the Evri courier network is used by Temu for the last mile in home deliveries, and my first orders arrived flawlessly in a matter of days; a credit is offered if deliveries don't arrive by the promised date.

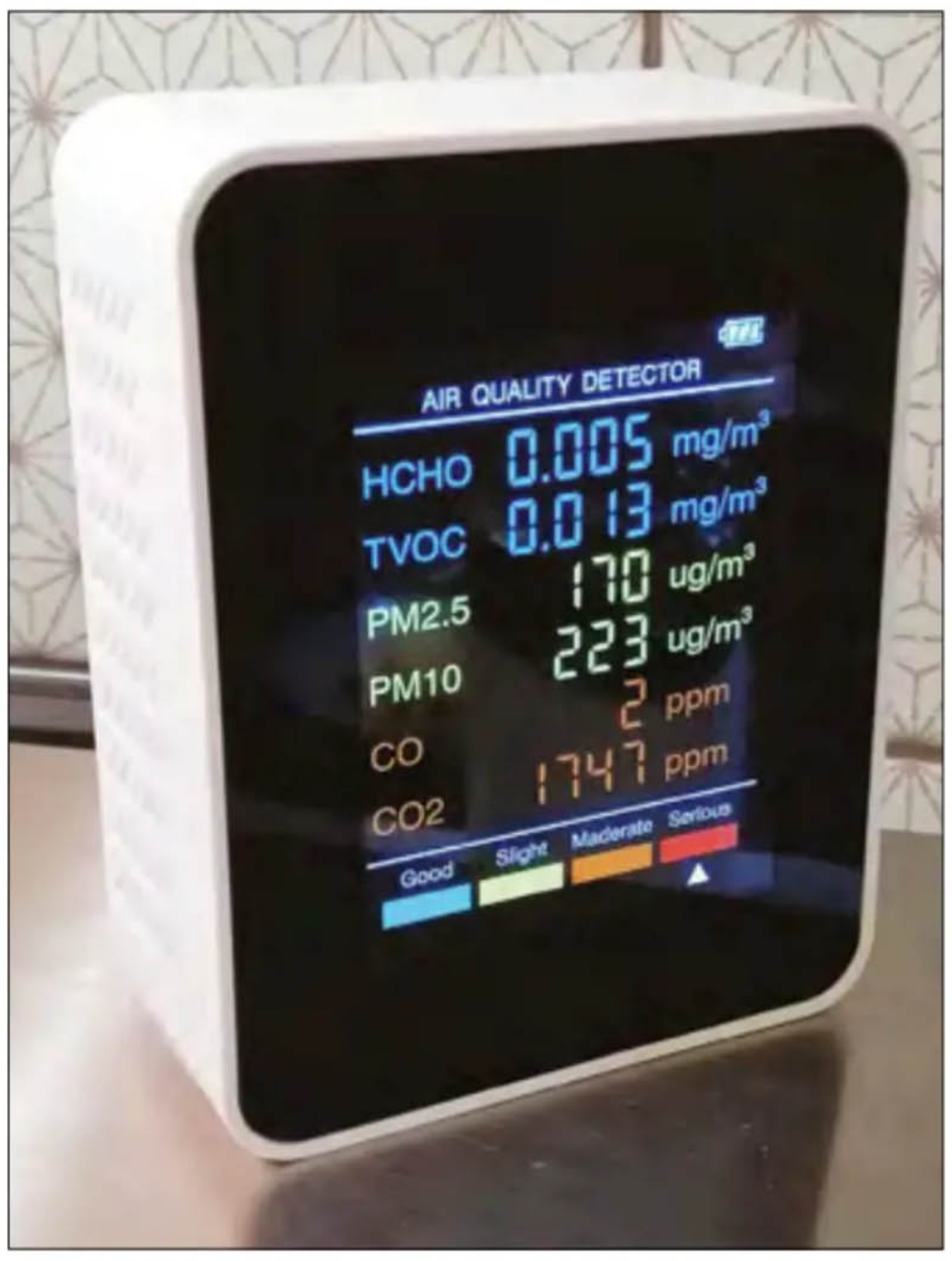
It's been hard to fault the service offered so far, and naturally the Temu app on a smartphone makes shopping more effortless than ever. One downside is the blizzard of emails that are sent by Temu and Evri giving order updates, tracking and delivery details, and customers can expect to see regular pop-up notifications with enticing offers and discounts tempting them to buy even more. The Temu website exhibits many 'dark pattern' behaviours (see *Net Work*, June 2023) that track your browsing or shopping patterns and nag you to buy now, before it's too late.

Chinese whispers

Much of the Chinese-made merchandise offered by Temu I would class as cheap and cheerful, of the sort that domestic mail order distributors would drop into a polybag along with a display header card and then quadruple the selling price. Apart from handy little doodads and knick-knacks, it wasn't long before I found enough of interest to fill a couple more orders. This included a 6-in-1 environment monitor that is widely advertised online, which displays Formaldehyde (HCHO), PM2.5 and PM10 (2.5- and 10-micron particulate matter), TVOC (total volatile organic compounds) as well as CO and CO$_2$ levels. The unit is self-contained, powered by a rechargeable battery and data is displayed on a colour LED. Although I didn't have high expectations of it, and a minority of reviews had been unfavourable, I decided it was worth a try at the offer price of £21 (£35-40 elsewhere) and one duly arrived on my doorstep a week or so later.

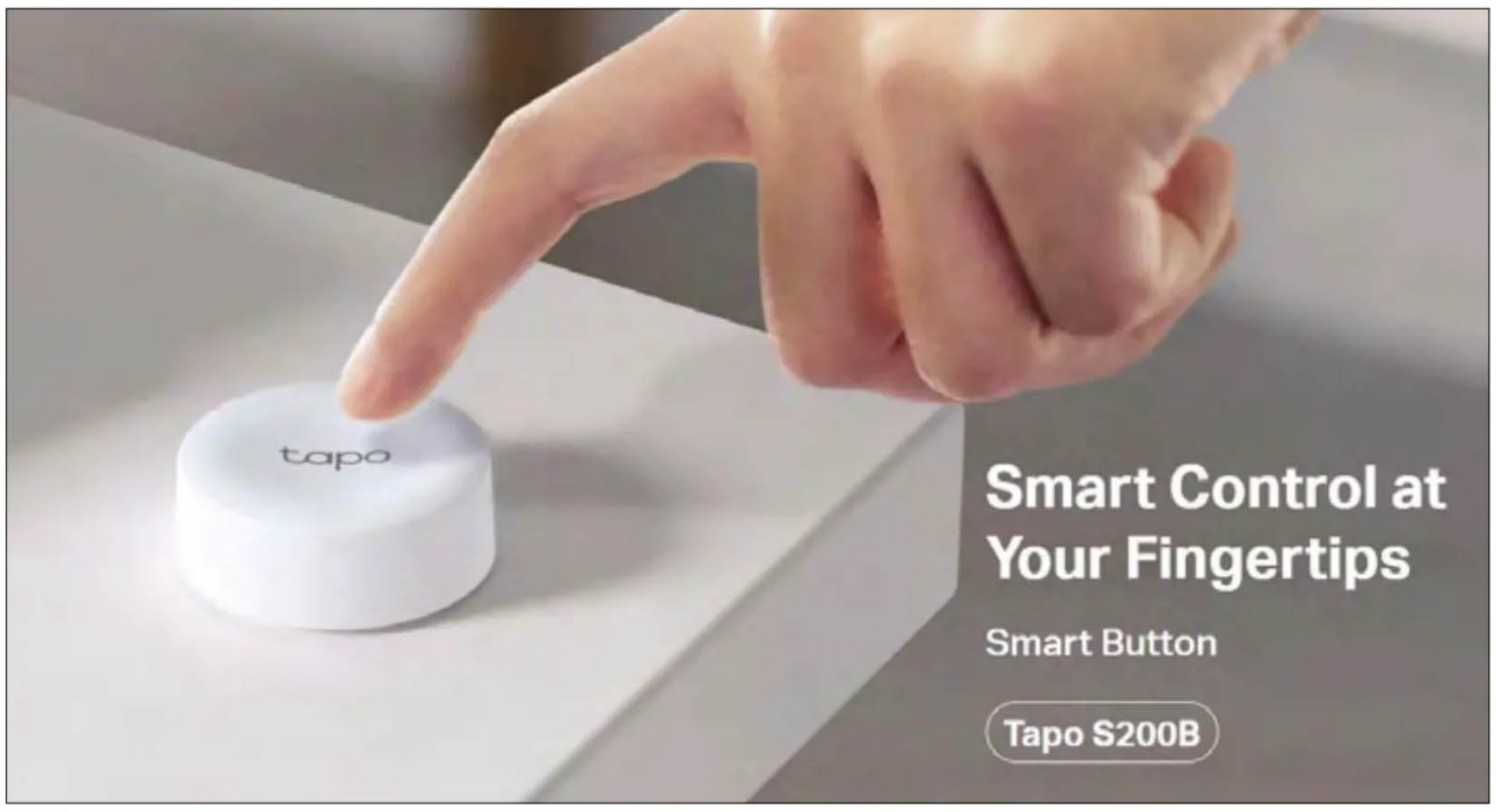
If nothing else, it's interesting to try sampling the air for pollutants in domestic situations, and when testing the monitor I did sometimes notice large changes in, say, the kitchen when various cooking appliances were in full swing. I also noted PM2.5 and PM10 readings that were broadly within the targets for particulate matter published by the UK Government: **https://bit.ly/pe-may24-pm**

Perhaps my rural location helps with air quality, and city dwellers may measure entirely different levels in their environment. Obviously, the monitor is designed for domestic use and is for guidance only; there's no way of checking calibration or its accuracy, but it is what it is and, given the low price, I didn't mind giving it a go.



This 6-in-1 environmental monitor is designed for domestic users and offers a digital readout of six factors. Readings shown when located in a busy kitchen.

Overall, first impressions of Temu have been surprisingly encouraging, and there have been no quality issues either, though I could do without those



The Tapo Smart Button S200 is an entry-level gadget to switch or dim compatible smart devices. The author had mixed success (see text).

tapo
Smart Water Leak Sensor
Drip & Leak Alert

Tapo's Smart Water Leak Sensor (T300) detects water leaks and drips, is rated IP67 and also has a built-in switchable 90dB piezo sounder.

nagging pop-ups appearing on my phone. You can visit **temu.com** or download the app through your usual app store. The rule of *caveat emptor* applies, but you might still find those introductory one-off offers irresistible!

Testing Tapo

As regular readers will recall, I've been testing out some entry-level smart devices marketed by TP-Link under the Tapo brand. In April's issue I outlined the Tapo H100 Smart Hub with Chime, a plug-in unit that resides in a mains outlet and connects through its own 868MHz (UK) wireless network to a range of smart devices such as contact sensors, a temperature/humidity detector and a PIR sensor. The Tapo app controls events and so-called 'smart actions' can be triggered when activated by a sensor.

Since writing last month's column I've tried a Tapo Smart Button (S200B) which enables manual control of Tapo smart devices, either by a single or double tap, or by turning the button instead. The wobbly plastic button is just over 40mm diameter and contains a 3V coin cell. Set-up is handled by following the instruction in the app, which was straightforward enough.

The button can be configured to control other compatible devices, or perform an action like sounding a chime on the plug-in hub. After a false start or two, I managed to switch a couple of Tapo smart lights on or off using a single button press. In theory, the colour or brilliance of a multicoloured LED smart lamp could be changed by spinning the button, but this concept didn't work very well on my own network, as the hesitant and 'stuttery' response often caused it to either lag or 'overshoot'. I soon abandoned that idea as a non-starter.

A non-slip pad (supplied) can be stuck underneath, presumably to stop it moving around when the button is operated. On a clean glass tabletop the button was too light (40g) and the non-skid base didn't hold it securely, making it impossible to turn the knob in a standalone mode. Due to the button's wobbly micro-travel operation I found it too easy to accidentally nudge it on the tabletop and activate a smart action. However, its built-in magnet allows attachment to a metallic surface, where it is held securely, and I found the button could be pressed or rotated without a problem. TP-Link includes a hefty metal disc and hardware that can be screwed or stuck on to a non-metallic surface – this was a much more secure option. Battery replacement is a bit fiddly, using the tiny mystery plastic shim supplied to undo the coin cell hatch. Expect a one-year battery life or longer.

Last month, I mentioned a 3D-printed holder made by an eBay seller to use the Smart Button as a doorbell in a sheltered location, advising that the button is not weatherproof and it could also be removed by anyone else 'in the know'. A wall-mounting version (S200D) is designed as a smart remote dimmer switch, but based on my own trials I personally wouldn't invest in it. Apart from offering a basic on-off control, the Smart Button may also find a use as a nurse-call chime, perhaps when caring for the elderly, but other dedicated options are available that are probably better suited to this purpose. Integration with an Alexa skill I found seamless but, annoyingly, Alexa isn't always totally responsive.

To round off my feature on the Tapo range, I also tried the 'Smart Water Leak Sensor' (T300), which is another low-cost device that requires the Tapo H100 hub. It felt a bit more substantial and could be used near water tanks, a washing machine or underneath a sink or shower tray. The underside carries two pairs of detector studs but, unlike many water leak alarms, the top is slightly dished and it has two more studs that can sense drips from above. After one or two attempts at adding the device in the Tapo app, I configured it to sound an alarm on the hub, and the sensor also has its own built-in switchable 90dB alarm; you can also link it to other smart actions. The T300 water leak sensor uses two AAA cells in a gasket-sealed compartment and a battery life of three years or more is claimed.

Overall, the budget Tapo range is aimed at domestic entry-level users, and the app is very user-friendly but set-up was sometimes a case of 'getting there in the end'. These smart sensors are available from the usual online sources, remembering that a smart hub H100 or H200 is also required.

Lotus blossoms

Looking at the year-to-date sales figures provided by Britain's Society of Motor Manufacturers and Traders (SMMT), we see that battery electric vehicles (BEVs) accounted for just 15% of the market, meaning the remaining 85% of vehicles sold so far this year still have petrol or diesel engines in them. Petrol cars still took nearly 60% of the market and hybrids of all types have accounted for about 21% so far this year.

Depending on who you ask, a hybrid car might offer 50 or 60 miles on electric

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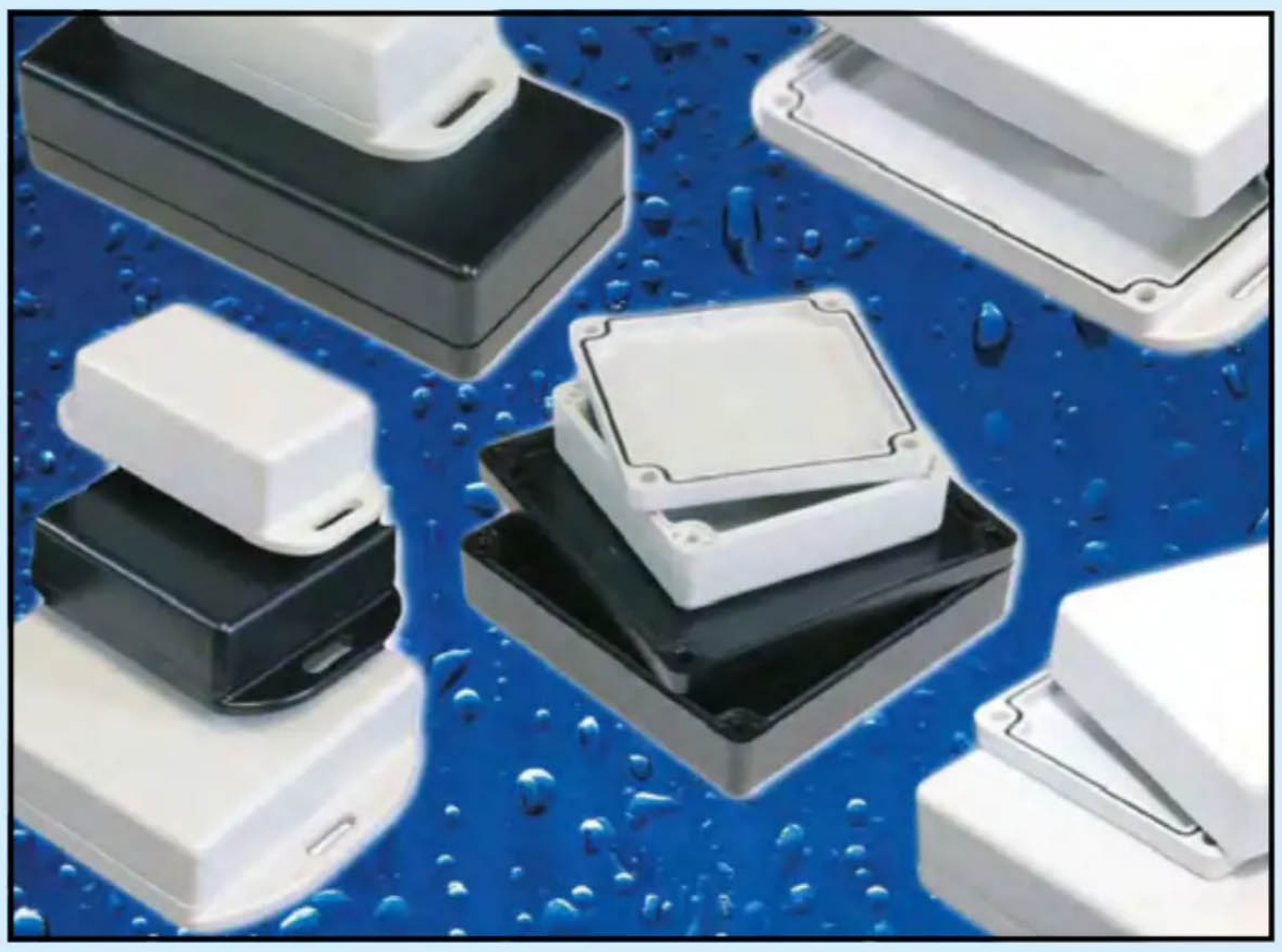


drive, which is handy for buzzing around town, but a whole new driving technique is needed to get the best out of these petrol-electric hybrid vehicles. The development of EVs in China is so intense that it's becoming impossible to keep up with trends. Waiting in the wings are yet more Chinese-made cars carrying British brands, including MG and Lotus. The latter was famed for its British-made sports cars: remember Tesla's first Roadster electric car was based on a Lotus Elise way back in 2006, and Elon Musk launched 'Starman' into space in 2018, where the car is still flying through space at 8,000 mph, see: **www.whereisroadster.com**

The new Chinese-backed Lotus Eletre EV is a snip at £90,000 to £150,000!

Now owned by China's Geely, Lotus is preparing to unleash an entirely new range of electric vehicles in the UK and Europe. From the outside, the new Lotus Eletre 'hyper SUV' (£90,000-£150,000) looks indistinguishable from many other Chinese electric or hybrid cars – it seems to me – while the new Emeya is a four-door GT sportscar that claims to be one of the fastest electric GTs in the world, achieving 0-62mph in under 2.8 seconds. Happily, British sportscar manufacturing will continue with the very attractive new Lotus Emira mid-engine sportscar (£60k+) due soon. The Lotus website is enough to make anyone dizzy, but you can see more of their new electric and petrol cars at: **lotuscars.com**

Geely has also partnered with Mercedes-Benz to produce premium EVs under the 'Smart' brand. Distinctive little petrol-powered 'Smart' cars have carved their own niche on Britain's roads, and a new electric 'Smart #1' compact SUV has now launched as a premium vehicle costing £36,000 on the road. Like every other electric vehicle, the Smart #1 dashboard is dominated by a touchscreen. Apart from anything else, manufacturers can update controls or debug them just by flashing new software upgrades, but opinions about the usability and safety of electric vehicle touch panels are very mixed. Not everyone is enamoured with the idea of tapping away at a touchscreen to control their vehicle, and there are increasing concerns about the problems of drivers' attention being distracted by the need to navigate through a touchscreen menu rather than simply reaching out to press a button or turn a knob.

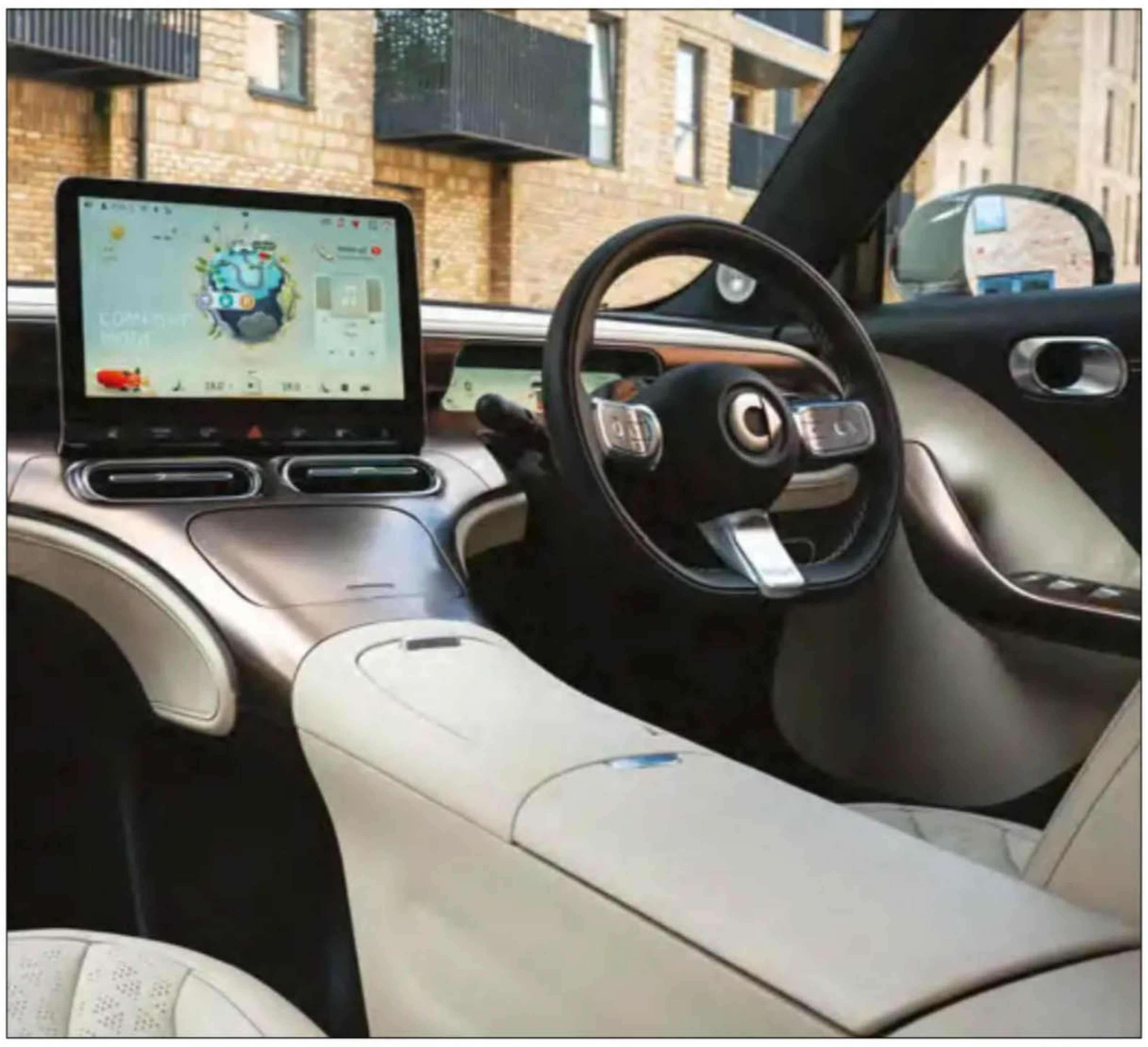
A spin in a Honda e:Ny1 electric car (see March 2024, *Net Work*) told me all I wanted to know: I found it hard enough as a passenger just to switch off the heated seats, and as we bumped along some country lanes I struggled to register a fingertip with a little icon on the impressively large screen, not helped by the lack of any haptic feedback.

Net Work reader Stephen Horsman sympathises. Steve writes: 'I've not long ago had a new VW Tiago with a touch screen infotainment centre. I have a slight tremor in my hand which makes touch screens difficult to use, but the worse thing is that they don't work at all with a gloved hand. Long live the mechanical switch!'

I mentioned in December 2023's *Net Work* how, by chance, I rediscovered my family's 1976 Opel Ascona saloon, a car bought brand new at a time when your scribe trundled along to attend evening classes as a teenager. The car is now an exhibition showpiece and I was thrilled to sit in it once again. The Opel's controls were dead easy: for example, the heater had up/down and hot/cold, and a simple knob controlled the fan speed. Pulling the knob out turned on the heated rear screen. The mains point is that all this could be done by 'feel' while I paid attention to my driving and pondered my homework.

Touchy feely...

Nowadays it seems that EV manufacturers are at last getting the message about the way touchscreens are becoming too distracting and unsafe for drivers. The Euro New Car Assessment Programme



The Smart #1car's interior has a flat control panel dominating the dashboard.

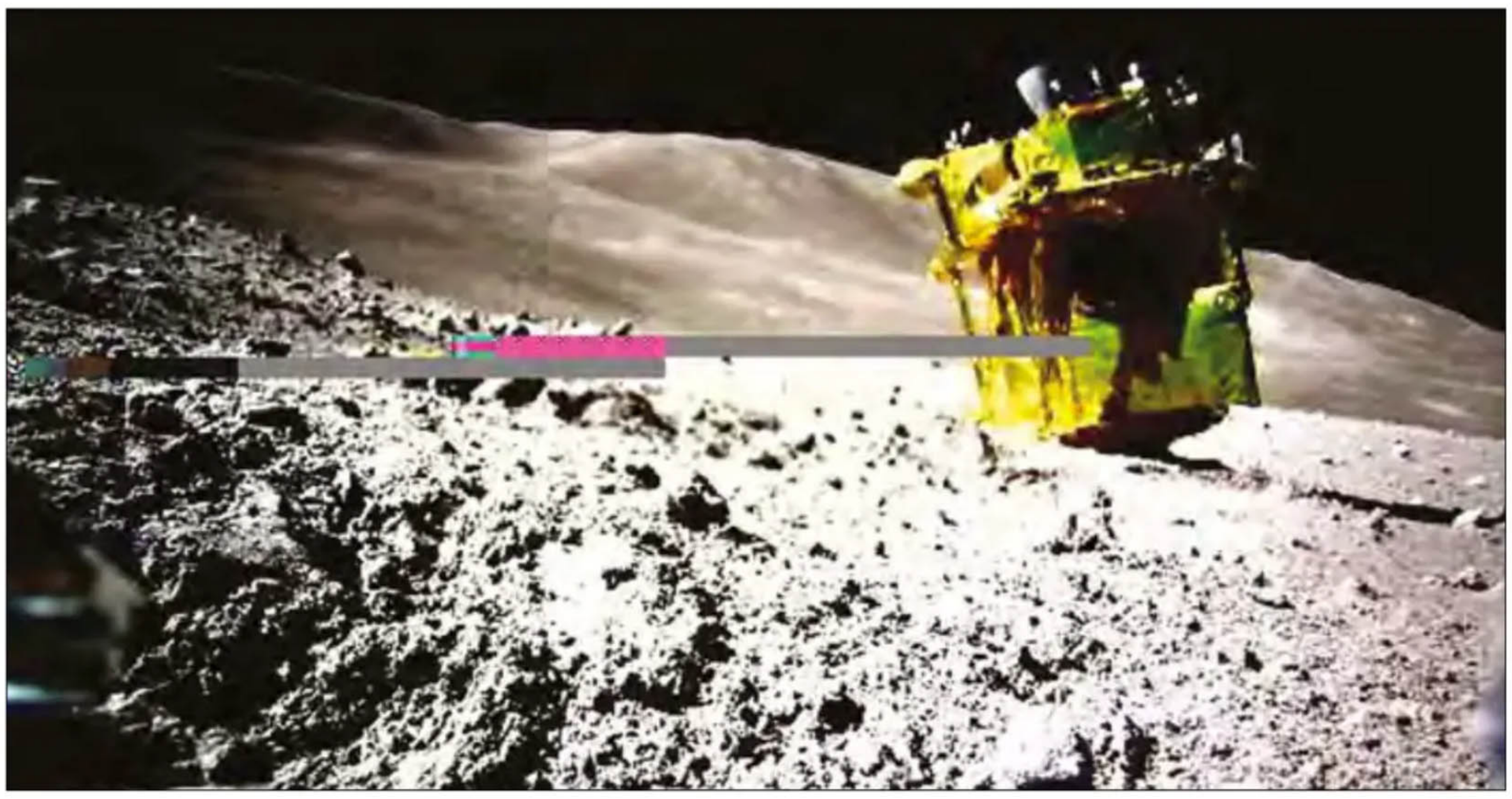
The Smart brand is best known for its quirky little petrol cars and the new Smart #1 is a compact SUV for the EV market.

(Euro NCAP) is the test body that awards new cars a safety star rating, and makers clamour to receive a coveted 5-star award. Euro NCAP has finally recognised that confusing and complicated touchscreens can cause drivers to take their eyes off the road for too long so, if car makers want to earn a 5-star rating, then from 2026 some key functions will have to be controlled by classic switches and knobs instead. Interestingly, Mazda Cars eschews altogether the use of large touchscreens and retains ordinary knobs and switches instead, an idea that may appeal to many motorists seeking to upgrade without tussling with touch controls.

EV drivers currently face plenty more practical problems, including punitive insurance costs and difficulties waiting for spares or costly repairs while Chinese EV brands get to grips with selling into the UK market. An excellent piece in *Auto Express* highlights these problems, with a BYD Seal proving almost uninsurable, they found, while GWM Ora was heavily criticised for a lack of spares. Major repairs that are cheaply done in China are unaffordable in Britain due to UK labour costs (as I know myself – I was charged £220 ($285) to fit four spark plugs!), and EV makers apparently don't understand that crash repairs must restore the car back to the manufacturer's standard – the kind of information that simply doesn't yet exist. The picture is one of Chinese EV makers desperately scrambling to ramp up after-sales service and support; the article is worth a read at: **https://bit.ly/pe-may24-aexp**

Hard cheese

In March's column I wrote about independently funded endeavours to land a small craft – the Peregrine Lander – on the Moon. Due to a propellant leak, the craft failed to reach orbit and was forced to burn up in the Earth's atmosphere, taking its payloads with it. As if to symbolise the frailty of our efforts, the payloads included human ashes transported courtesy of Elysium Space (qv) and other plaques and mementoes from around the world, destined for commemoration on the Moon. Russia had tried to land its Luna-25 at the Moon's South Pole the previous August, but the vehicle was lost during final approach. India then accomplished a spectacular and historical South Pole landing with its Chandrayaan-3 (Lunar Vehicle 3) lander that same month.



SLIM pickings: image of the Lunar surface taken and transmitted by LEV-2 (Image © JAXA/TOMY/Sony Group Corporation/Doshisha University.)

Japan's 'Moon Sniper' mission carrying SLIM (Smart Lander for Investigating Moon) has been designed for landing accurately within 100m of the target on the Moon's surface. This mission unfortunately nosedived in January – a suspected engine failure caused the craft to land literally face down on the Moon, nonetheless within 55 metres of its intended target. Unfortunately, this crippled its ability to generate power from its solar arrays, but even so, two tiny robots – Lunar Excursion Vehicle (LEV-1) and Transformable Lunar Robot (LEV-2) – were successfully released just prior to touchdown and successfully conducted some trials on the Moon's surface. Japan's Aerospace Exploration Agency JAXA points out that LEV-1, weighing just 2.1 kg, communicated directly with Earth from the Moon, and is considered to be the world's smallest and lightest example of direct data transmission from a distance of some 380,000km. LEV-2 managed to take a snapshot of the stricken vehicle.

Undeterred by recent setbacks, another Moon-bound mission by a joint venture between NASA and Intuitive Machines (IM) launched in February on board a SpaceX Falcon 9, carrying IM's Nova-C lander named 'Odysseus'. This time, the craft did land successfully on the Moon's surface, but then it had the misfortune of toppling over. Despite this, it was the first commercial vehicle to successfully land on the Moon. Odysseus closed down a few days later on the 29 February – one giant leap year for mankind.

Last, in my space news roundup, the plucky Ingenuity helicopter that NASA's Perseverance rover launched on Mars (reported three years back in *Net Work*, May 2021), has finally run its course. The hovering vehicle managed an astonishing 72 flights on the dusty red planet, far more than was ever intended. A broken rotor blade was later spotted by an imaging camera on board the Perseverance. NASA's superb website

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Odysseus, a NASA/Intuitive Machines craft captured this image approximately 35 seconds after pitching over during its approach to the Moon landing site. (Image: Intuitive Machines)

contains a wealth of resources related to their Mars missions – be sure to take a look at: **https://mars.nasa.gov**

Rejected scripts

My thanks to regular reader David Hicklin who writes: 'Having just read *Net Work*, March issue and especially the bit 'Bad news days', have you ever seen how many scripts run on a news site that come from third-party websites? I use Firefox and one of my best friends is the add-on 'NoScript' and it has an absolute fit at the number of third-party scripts that run on these sites. I'm attaching a sample from a local news site which is a typical example. I think these are a far bigger issue than cookies, and let's not start about websites that give you the options to set the cookie settings, maybe 75+ of them, one setting for each external partner!'

Thanks for the tip-off, David. In March's column I explained how third-party cookies are gradually being blocked by web browsers in favour of only allowing first-party ones; ie, those that originate from the website you're visiting at that time. This is actually seriously affecting news media websites and the wider industry, because it's cookies that give them the ability to target their advertisers' messages at 'interested' website visitors. Adverts that are irrelevant to their viewers are obviously worthless, and advertisers won't pay if wasted traffic is squandering their budgets needlessly. Consequently, the news site's advertising clients will walk away, taking their advertising revenue with them. To compensate for the drop in advertising income, visitors will increasingly see pay walls adopted, or they'll either pay to see a site or be forced to accept adverts instead. I agree that those cookie opt-in pop-ups are now a major nuisance. Quite often I can't be bothered working through all the options given so I move on elsewhere.

I mostly use Firefox too, and previously I've tried the Ghostery extension to flag up trackers and block ads, but I had problems with my browser being slowed down. I noted more than 100+ running on some web pages. You can install NoScript, as David suggested, from **https://noscript.net** and Ghostery is still available from **https://www.ghostery.com**

Amazon Warrior

Amazon remains a key go-to site to purchase pretty much anything under the sun, but one emerging issue is the problem of book piracy, as I recently discovered. It appears that some niche reference books, including my own *Basic Soldering Guide*, were stolen in their entirety and re-published using entirely bogus pseudonyms. In my case, more than a dozen books on soldering suddenly popped up on sale, all the same size, style and contents (mine) but with different cover images and authors' names. Fortunately for me, I was alerted by one book review which included photos of me holding my own soldering iron! It was a concerted effort to cash in on the book, with sophisticated generative text containing stolen keywords being used to hijack 'my' search traffic. To be certain, I ordered copies of each one, totalling £150 worth.

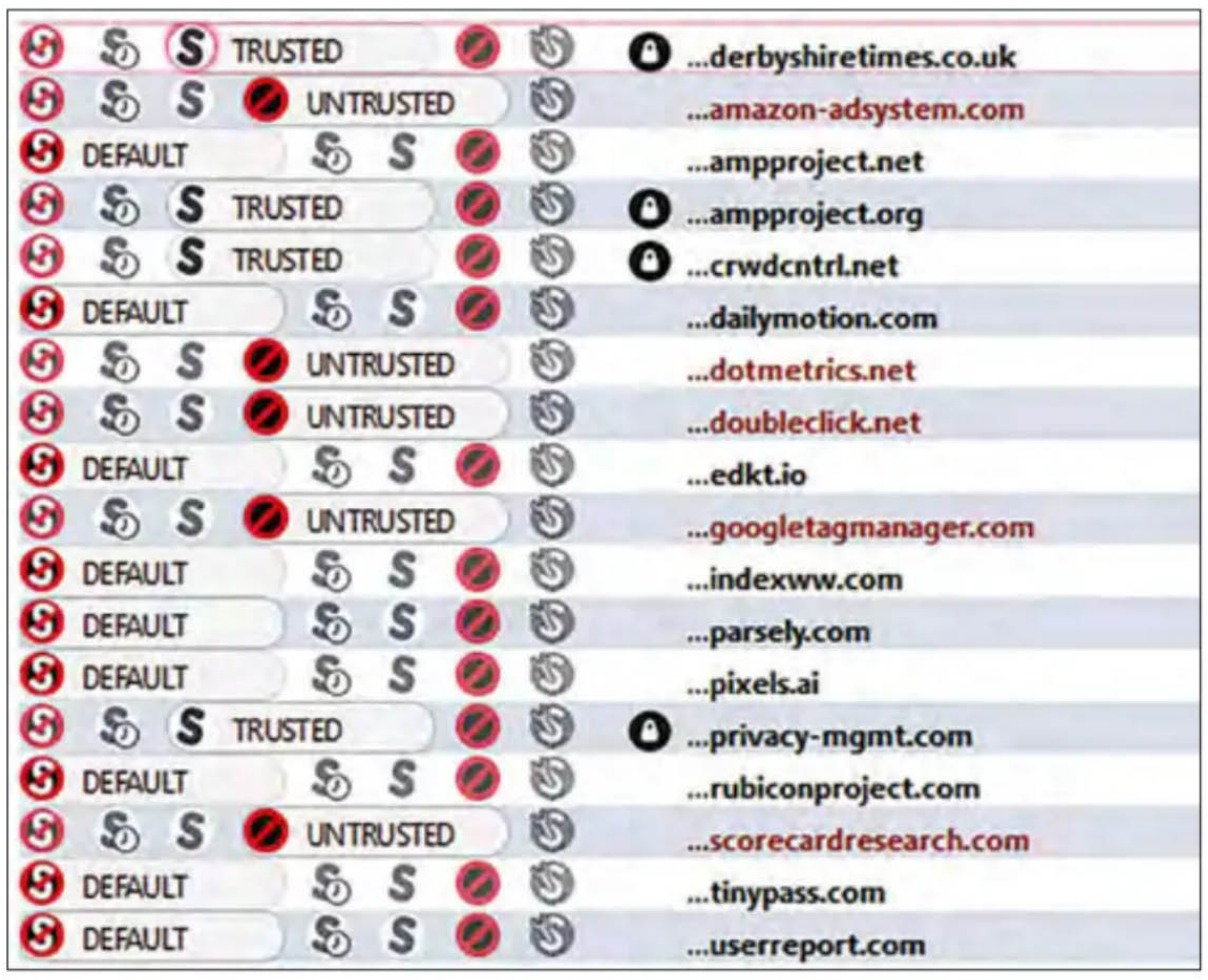
Copyright infringement is a very expensive and time-consuming problem to police. As the perpetrator of this scam could be located anywhere in the world, the only practical step is to alert Amazon using the 'Report an issue with this product' link found on each item page, and fill in an online claim. This drudgery took up a whole day but, to be fair, once notified Amazon removed the stolen books within 30 minutes.

Then I noticed similar shenanigans with certain other book titles that used the same style of book covers, with false names. Searching for a particular title on coding and programming threw up more than a dozen near-identical candidates, all selling at around £12 each and pirated from another (as yet unknown) work. The free preview sample reveals similar opening paragraphs. The best a third party can do is report it as counterfeit, but it's infinitely more effective if the original work can be cited as evidence.

Such is the quality and scale of the scam that I suspect AI is being used to re-write book descriptions and re-submit them for publication using Amazon's print-on-demand service or KDP (Kindle Direct Publishing). So next time you're searching Amazon for books, watch out for similar-looking niche titles or book covers on Amazon – these are scammers trying to cash in by stealing legitimate work. By the way, readers can buy the (real) *Basic Soldering Guide* handbook direct from our own bookshop at an advantageous price.

That's all for this *Net Work* roundup – see you next month!

The author can be reached at:
alan@epemag.net



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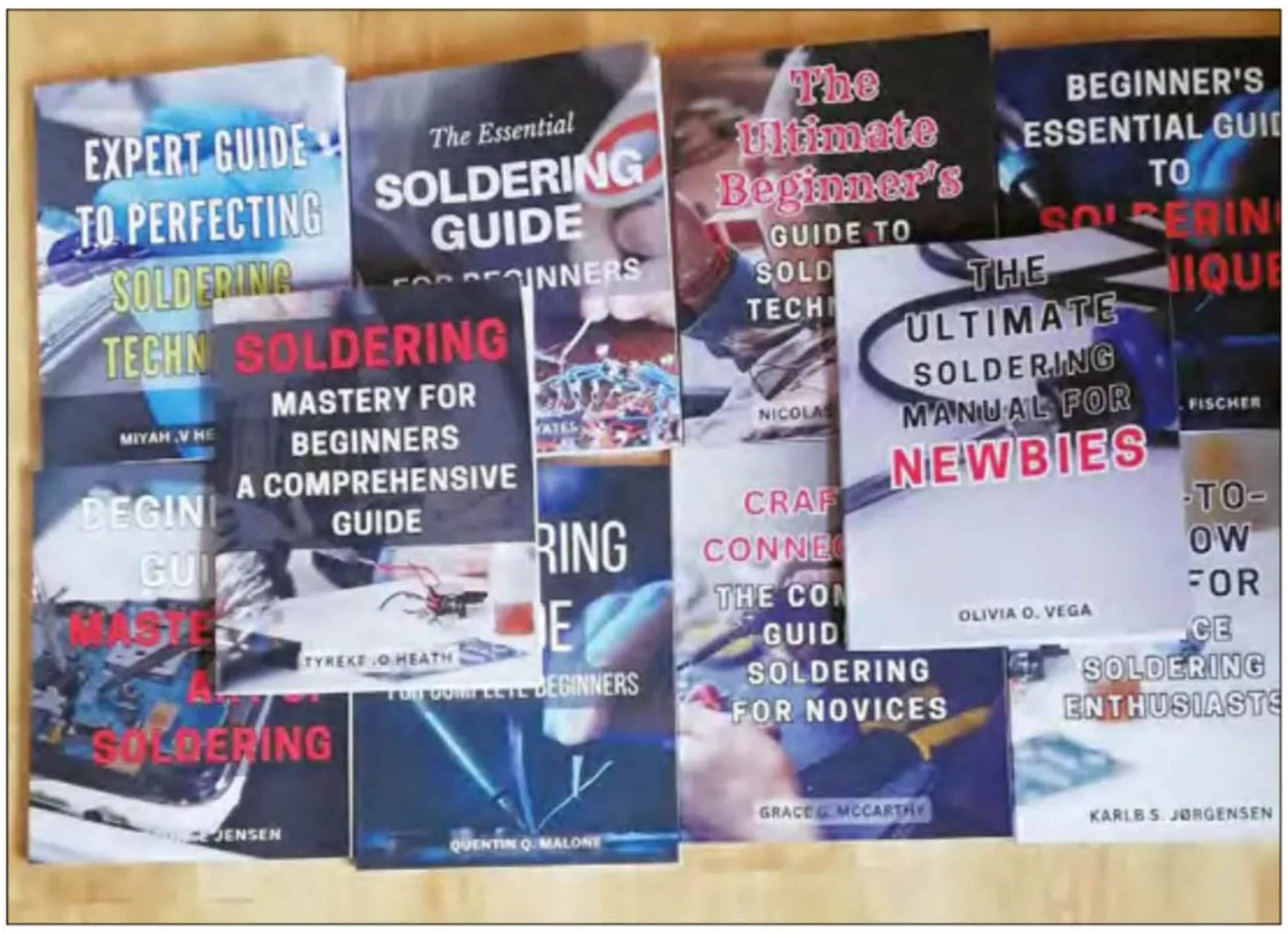
An insight produced by NoScript showing some of the scripts running behind the scenes on a busy news website. (courtesy, David Hicklin.)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OLIVIA O. VEGA
CRAF CONNE THE CO GUID SOLDERING FOR NOVICES
TO- OW FOR CE SOLDERING ENTHUSIASTS
BEGIN GU MASTE A SOLDERING
RING E FOR COMPLETE BEGINNERS
JENSEN
QUENTIN O. MALONE
GRACE C. MCCARTHY
KARL B. S. JØRGENSEN

All 15 of these pirated *Basic Soldering Guide* books were spotted on Amazon by the author before being removed from sale. The same ruse is currently affecting other book titles.

The Fox Report

Barry Fox's technology column

Cloning drives the easy way, plus more news on scams

Danish electronics company Sandberg (slogan 'IT is for everybody') makes clever and well-designed gadgets with a real purpose. I recently tried Sandberg's 'Unusual hard drive tool' because it makes a nice fit with our recent articles on making PCs perform much better by replacing an 'old-fashioned' spinner Hard Disk Drive with a new SSD (Solid-State Disk).

To make the HDD-to-SSD replacement you first need to clone (not simply copy) the existing operating system on the existing HDD to a new and empty SSD. This can be tricky and risky because making a mistake in the cloning process can easily result in wipeout, with the old HDD and new SSD both empty. Sandberg's 'unusual' tool makes cloning as safe and easy as it can be; near risk-free in fact. The same tool also makes it much easier to work with 'bare' HDDs and SSDs, storing and reading data to and from discs of both types.

Smart connector

The Sandberg tool is really just a very smart connector strip, powered with a separate 12V supply. The strip has SATA and NVMe sockets for plug-in connection to standard 2.5-inch and 3.5-inch SATA spinner drives and SSDs of the type that slot straight into modern computers and peripherals. Connection of the tool to a PC or mobile is by standard USB-A or USB-C cable. No screwdrivers are needed. Rather fiddly rubber plugs do the job of screws.

Two drives, HDD and SSD, can be connected to a computer simultaneously or separately, with reading and writing possible to both. But the tool also has on-board software that lets it clone directly from one drive to the other, without the need to connect to a computer. A physical switch controls the direction of cloning, HDD to SSD or vice versa. This is what makes wipeout mistakes far less likely.

Sandberg says that because the tool supports USB 3.2 it's theoretically possible to achieve transfer speeds right up to 10 Gbps. But this will of course depend on the drive specs.

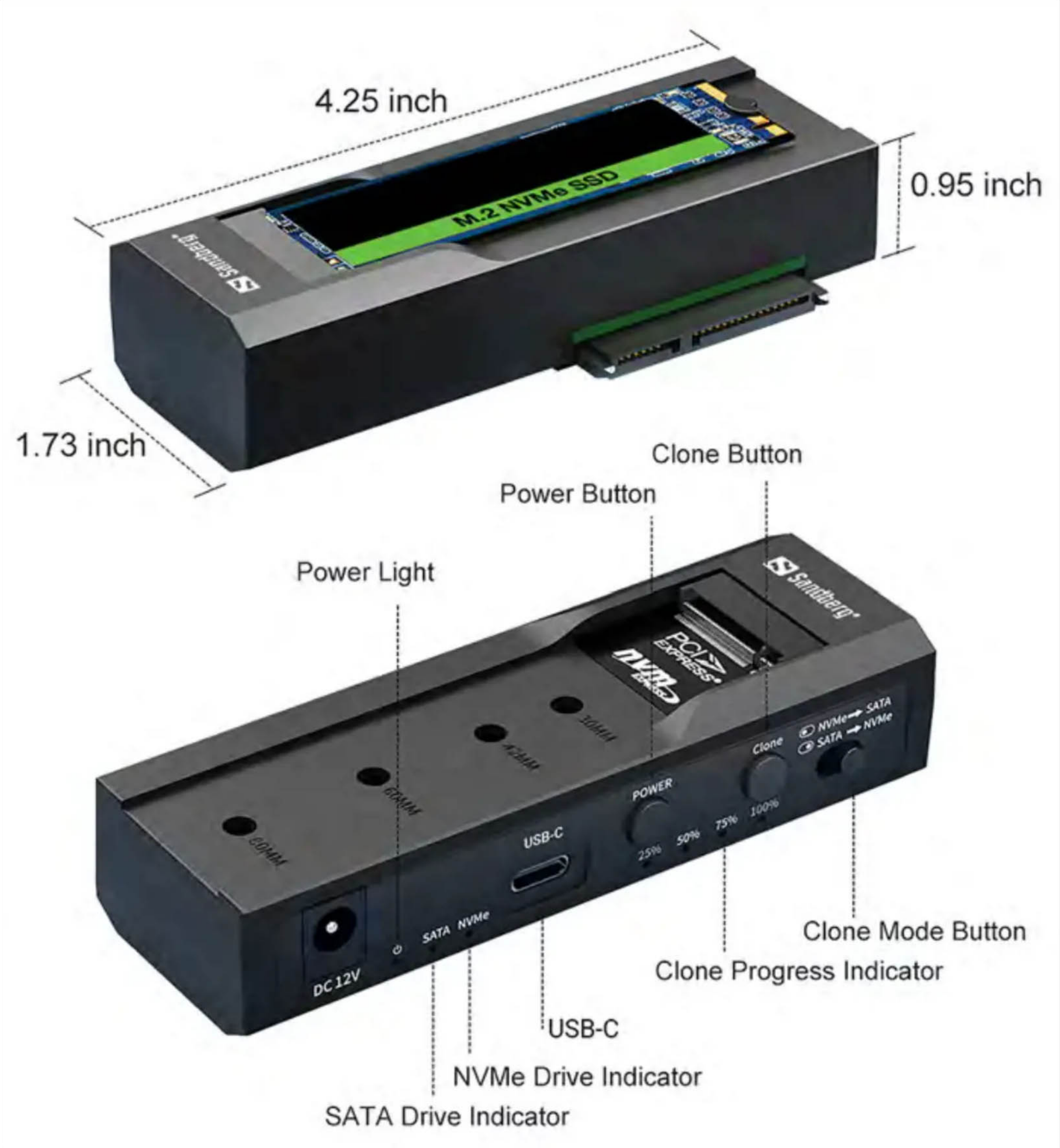
Anders Partida Petersen, Brand Director at Sandberg, is realistic when he admits the new tool 'may well seem like something for nerds'. But I guess that term covers many of our readers! I'm pretty sure computer service centres will love it too.

I've tried it and certainly love it. I just wish I hadn't previously wasted my money on a multi-bay HDD dock that looks good but has corrupted some of my HDDs, and also on two-bay HDD docks which are far less use than the much neater Sandberg tool.

The USB 3.2 cloner and dock costs £59.99, and in addition to SATA supports SSD fitting types M.2, NVMe and M Key, in sizes 2230 / 2240 / 2260 / 2280.

Scammer update

We have already warned that scammers have moved on from selling fake capacity USB memory devices that store far fewer megabytes than claimed to SSD drives that store far fewer gigabytes than claimed. Fortunately, there are easy-to-use free apps that test capacity. So far, the tests have been lengthy, but a newish free app plays clever tricks to shorten the test time. It randomly tries to read and write data at widely spaced sections of the memory map. So, it quickly fails if real capacity is lower than it should be. The drive is then red flagged for junking or more detailed testing. For further details, see: **https://bit.ly/pe-may24-drv**



Fox tested and approved – Sandberg's 'Unusual hard drive tool' makes cloning drives straightforward, easy and safe.

It now emerges that scammers are also selling fake USB hubs. Devices that are labelled USB 3.0 or simply equipped with the blue lip sockets that are supposed to guarantee USB/3.0 SuperSpeed performance, are actually USB 2.0 or 2.1. Again, fortunately, there is a simple free test, called 'USB Device Tree Viewer'. Just install the app on your computer and plug and unplug hubs, one by one. The app then displays which devices are 2.0, 2.1 or 3.0.

I have already found several hubs, bought online, that have blue lips but USB 2 speeds. USB Device Tree Viewer also provides useful information on every USB device that is hard-wired or plugged in – see: **https://bit.ly/pe-may24-usb**

Card scam - not what you think!

Meanwhile, news is now breaking of a new high street scam for which there is no useful IT app cure – so self-protection is the key. It seems the crims are 'borrowing' gift cards, for food and services like music and movie streaming, from supermarket checkout racks. They then secretly copy the card validation code and put the card back in the rack. When another customer innocently buys the card and loads it with credit, the crim can use the previously stolen code to steal the credit.

So, from now on I shall buy my cards only from stores that keep them securely 'behind the counter' and thus unavailable for 'borrowing'.

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tekkiepix pic of the month
U-matic video cassette recorder

U-Matics were not pretty, they just did the job, and loaded faster than open reel.

Early CD discs were often edited and mastered on U-matic systems.

Here's a good 'pub quiz' question for *PE* readers of a certain vintage: 'When did the first video *cassette* recorders go on sale, and what was the name of the manufacturer?' Betamax, from Sony, in 1975? Wrong. VHS from JVC, in 1976? Wrong, again. So perhaps it was a bit of a trick question?

Panasonic was ahead of VHS with a VCR called the Quasar VX 'The Great Time Machine', born 1975, but it died soon after – and not just because the marketing team hadn't realised that just about everyone associated the label 'VX' with nerve gas. So, was that one first? Sorry, wrong again; and even though Dutch Philips had stolen a march on the Japanese with the N1500 VCR in 1972, that's still not the right answer.

The first working video cassette recorder was the U-matic, developed by Sony, with Panasonic and JVC joining in for a joint launch in 1971.

It's true that the first U-matic recorders needed a bolt-on tuner and output circuitry to feed into the aerial socket of a home TV. It's also true that the U-matic system was initially adopted by professionals rather home users because of high cost and the lack of an easy connection. Neverthless, U-matic became a must-have trophy gadget for well-heeled homeowners, and recorders were soon available with built-in connectors for home TVs.

U-matic cassettes held ¾-inch tape, rather than the 1-inch tape used for open-reel recorders and ½-inch tape used by Beta, VHS and the Philips and 'nerve gas' systems. But most people neither knew nor cared what kind of tape was in the cassette.

Until then, home video wannabees had had to struggle with open spools of very expensive video tape that needed careful threading round a spinning head drum. Touching the tape could spoil a recording – and anything less than precision threading could wreck the delicate video heads.

U-matic cassettes only ran for an hour, but so did the Philips cassettes and the first Sony Betamax tapes. Sony's boss Akio Morita initially saw no problem with this because back then most Japanese TV programmes only ran for an hour anyway. Threading video tape became a thing of the past, just as threading audio tape was no long necessary once Philips had launched the audio cassette in the 1960s, and Americans slapped 8-track cartridges in car players.

All the the proud owner of a U-matic player had to do was 'post' a sealed cassette into a letter-box slot, and a clever mechanism hidden inside the player automatically laced it round the drum.

JVC marketed U-matic recorders as U-VCRs that plugged into a 'regular TV' and recorded 'off-the-air TV programs' under 'full remote control'. Meanwhile, however, JVC was working secretly on the less expensive VHS system.

For many years, U-matic was a standard convenience tool for broadcasters, programme makers, business teachers and TV advert producers. Early video cinemas used U-matic tapes, and security services used them for secret training videos – as one UK journalist found out to his cost when he bought some cassettes from a tech jumble sale and thought the contents looked suspicious. Soon after he wrote about them in a specialist video magazine, promptly followed by a knock on his home door and a bunch of big men with security IDs confiscated the cassettes.

In the early 1980s U-matic cassettes were used to store digital audio and became the *de facto* standard tool for mastering Compact Discs (CD). The cassette tape stored digital audio packed inside a video signal. As far as the U-matic recorder was concerned it was just another signal.

More consumer-friendly (smaller, lighter and cheaper) VHS and Beta decks could do the same job, but U-matic recorders and tapes were far more rugged.

Practical Electronics is delighted to be able to help promote Barry Fox's project to preserve the visual history of pre-Internet electronics.

Visit **www.tekkiepix.com** for fascinating stories and a chance to support this unique online collection.

BY ALAN CASHIN

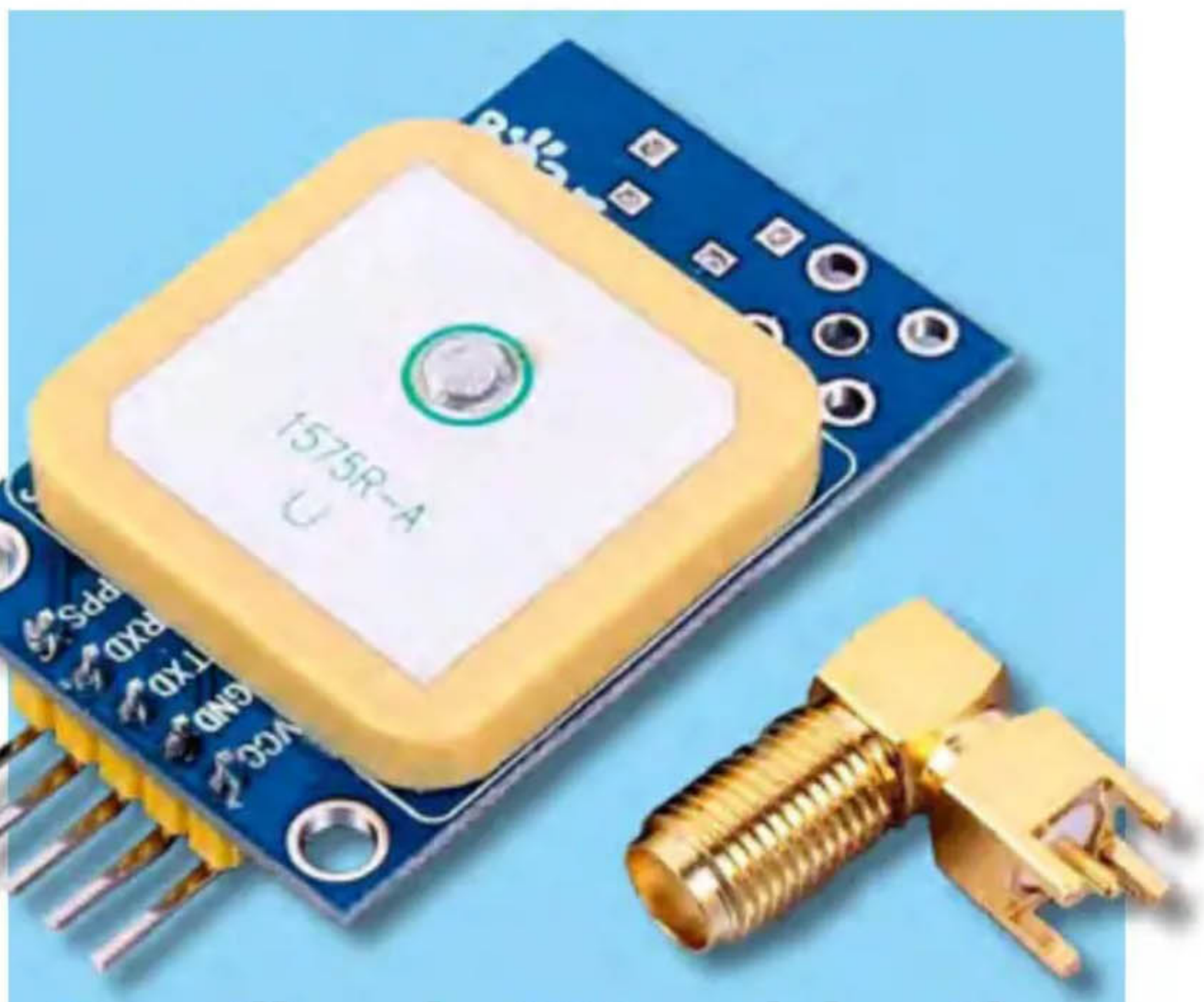
GPS-Disciplined Oscillator

The GPS-Disciplined Oscillator (GPSDO) is built almost entirely in software, so it only requires a PIC, an oven-conditioned crystal oscillator and a few other supporting parts. It provides an extremely accurate 10MHz signal with an error in the parts per billion range.

There are a few situations where having a very accurate frequency is essential. Many pieces of test equipment, such as oscilloscopes and spectrum analysers, have an internal 10MHz reference that's accurate to within a few Hz (around one part per million). They usually have an input socket for a more precise external signal source for operating with much higher precision.

As people explore high and higher operating frequencies, reference accuracy becomes more critical. An error of 1 part per million (ppm) at 7MHz is only 7Hz, hardly noticeable in a single-sided band (SSB) signal). But at 5GHz, the same error is 5kHz, enough for the signal to not be received at the expected frequency.

Global Navigation Satellite System (GNSS) satellites have accurate atomic clocks onboard that are adjusted by signals from ground-based master clocks. The satellites broadcast signals with precise timing that allow a GPS receiver to determine the receiver's location and the time. Many GPS receiver modules generate an accurately timed one pulse per second (1PPS).



You will need a GPS module with an SMA socket and 5-pin header, such as the Neo-7M shown above. Make sure the header is wired as per Fig.2.

This project describes a GPS-Disciplined Oscillator (GPSDO) that uses the 1PPS signal to adjust (discipline) the frequency of a 10MHz oven-conditioned crystal oscillator (OCXO). The output is accurate to a few parts per billion (ppb) at worst, and normally 1ppb or better.

GNSS and GPS

GPS refers to the constellation of navigation satellites launched by the US government but is sometimes used to describe any positioning system that uses satellite data for navigation.

Last century, the only useful constellation was the GPS constellation. More recently, many nations have launched their own satellite constellations, such as GLONASS (Russia), BeiDou (China) and Galileo (Europe).

The term 'global navigation satellite systems' (GNSS) refers to all the available constellations. Many 'GPS' receivers are actually GNSS receivers and can use data from several constellations. This means the receiver is more likely to pick up usable signals since many more satellites are available to it.

However, there are differences between constellations, and the receiver may be less accurate if it switches between constellations.

Designing a GPSDO

I first became interested in GPSDOs after reading the *GPS-Based Frequency Reference* by Jim Rowe (see *PE* (*EPE*) April-May 2009).

In theory, a microcontroller could replace most of the discrete components. To test this, I designed a GPSDO that used a PIC16F628A. It worked, but was too elaborate.

I decided to improve my old design after seeing Tim Blythman's *Programmable GPS-synched Frequency Reference* (October and November 2019), which has an accuracy of ±100ppb.

The aim of this was to create a useful and inexpensive GPSDO that could deliver 10MHz into 50Ω with a maximum error of 0.01Hz.

It is based on a cheap CTIOSC5A2B02 oscillator, a PIC16F1455 microcontroller and a 74HC04 hex CMOS inverter running from a 5V supply.

The GPS module I used was the cheapest available, the u-blox NEO-6 (possibly a clone), using an active antenna with a 3m lead. There was no need for any display; anyone with a smartphone can see their position and get accurate time, so such a display is redundant. The operational status is indicated with a single LED.

This prototype system performed well enough to justify creating a PCB, and several were built. However, it was overly sensitive when connected to other equipment.

Another problem was that I had not designed the PCB with any enclosure in mind, so it needed a larger enclosure than necessary. And people may prefer a 12V supply rather than a 5V supply.

Consequently, I designed the revised PCB that is presented in this article. The oscillator is substantially independent of the rest of the circuitry. The PCB fits a UB3 Jiffy box and runs from 12V DC.

How it works

The GPSDO is designed to use a 1PPS signal and NMEA (National Marine Electronics Association) serial messages delivered at 9600 baud. Many GPS receivers have these capabilities in a wide range of prices and feature sets.

The GPSDO counts the cycles of the local oscillator between successive 1PPS signals. Any deviation from ten million causes a change in the control voltage to ensure there are ten million cycles per 1PPS. The oscillator is locked to the 1PPS signal, and so it can be used to accurately time long periods, as well as provide an accurate frequency.

In the long term (days or weeks), a GPS receiver provides a very accurate time signal. But in the short term (second to second), there can be variations due to receiver design, signal reception and other factors. Many GPSDO implementations use specialised GPS receivers designed to minimise these variations and allow for relatively straightforward control strategies.

This GPSDO was designed to use low-cost GPS modules that deliver a time signal with significant short-term variations. To overcome this, the processor uses the average of many 1PPS signals to produce a more accurate result. The oscillator control is then varied at intervals of many minutes rather than continuously. The default is 512 seconds, but this can be changed through the user interface (UI). This approach offers both benefits and shortcomings.

One benefit is that the GPSDO can evaluate its own performance. Because the control is varied by a known amount after a known interval, a maximum error can be attributed to the oscillator output before the correction is applied.

The drawback is that the local oscillator's phase (the amount of lag or lead) can be greater than it would be with a PLL (phase-locked loop) design. But like a PLL design, the local oscillator is locked to the 1PPS signal in the long term.

In more detail

I chose a PIC16F1455 for the microcontroller as it has several useful peripherals. Its clock signal is the 10MHz output of the reference oscillator, which allows the micro to count the 1PPS pulses directly. The processor has a PLL to multiply this by 4, giving an internal 40MHz clock. Some of the inbuilt peripherals can use this clock; in this case, they are the 16-bit timer Timer1 and the 10-bit PWM (Pulse Width Modulator) generator.

Timer1 is used to measure the arrival time of the 1PPS signal. The 1PPS signal is one input to a comparator, with the other set to 1.9V from an internal voltage reference. The 1PPS signal swings from 0V to 3.3V, so the comparator can easily detect it. The comparator is set up to gate (pause) Timer1 when the signal arrives.

Another timer (Timer2) is used to count 10 million cycles, then start Timer1 at a known point. Since Timer1 is clocked at 40MHz, the interval until it is stopped is known to within 25ns. This is compared to a target arrival time, so it can determine if the pulse arrived early or late compared to the local oscillator. From this, we can deduce whether the oscillator is running slow or fast.

25ns is a sufficiently short interval for timing when using a low-cost GPS module. The 1PPS is generated from the GPS module's internal clock, which is not necessarily a multiple of 10MHz. Consequently, the pulse will not arrive precisely on time, but will appear to jitter around the correct value.

The jitter effectively randomises the arrival time so that accumulating the arrival times over a period gives a statistically more accurate average arrival time. Also, the 1PPS pulse timing is affected by atmospheric conditions, the transition between GNSS constellations and other effects, so measuring to better than 25ns yields little improvement.

The oscillator frequency can be varied by a few hertz on either side of 10MHz, based on a control voltage applied to the oscillator. The OSC5A2B02 has a nominal control voltage of 2V±2V and a sensitivity of around 0.1V/Hz. The PWM peripheral generates the required voltage, with its output going through a filter with a time constant of over a second to eliminate all traces of the pulses.

The output pulses of the PWM unit are at 40kHz, with the pulse width variable from 0 to 25µs in 25ns increments. If the pulse width is only changed when a change of control voltage is required, there would be 1000 voltage steps between 0V and 5V, which would change the frequency in increments of 5ppb. This is too coarse to be helpful.

The traditional way to tackle the problem is to add more hardware. Typical solutions are to use PWM over a smaller range and have a potentiometer to make a coarse adjustment; combine the output of two PWMs, one for coarse control and one for fine control; or use an external DAC (digital-to-analogue converter) with 16 bits (or more) of resolution.

This GPSDO solves the problem in software by dithering the pulse width on every pulse. Selected pulses are made 25ns longer. The base number for this is a 24-bit number, allowing the control voltage to be varied in increments of less than 1µV. This is far finer than required, but as it is generated in software, it is effectively free.

The unique pulse stream repeats more than twice a second, so the heavy filtering is adequate to remove any artefacts created by the dithering.

More capabilities

All a GPSDO has to do is time the arrival of the 1Hz pulses and adjust the control voltage to correct any deviation of the oscillator from 10MHz, as described above. However, it is desirable to be able to determine if the GPS unit is generating valid pulses, measure the GPSDO's performance, and indicate to users that it is functioning correctly (or not).

The GPS module generates NMEA messages as 9600 baud serial data (the micro can be programmed to handle the less common 4800 baud). The GPSDO decodes the messages, looking specifically for $xxRMC messages (xx because some modules output $GPRMC [GPS], some use $GNRMC [multi-constellation] and so on).

RMC is the recommended minimum message, so almost all GPS modules will deliver it. One field in the message indicates if the GPS has a valid location fix. The GPSDO ignores the 1PPS pulses if the fix is not valid. Although not necessary for GPSDO operation, other messages are decoded to obtain data useful for logging such as the date and time.

The GPSDO uses a single LED to indicate its status. The LED has patterns for error conditions, startup stages and operational status. When the OCXO is locked to the GPS 1PPS signal, the LED repeats a pattern once per second. A single 50ms flash indicates the OCXO should be within 1ppb of 10MHz. Otherwise, there are two closely-spaced 50ms flashes indicating the accuracy is uncertain.

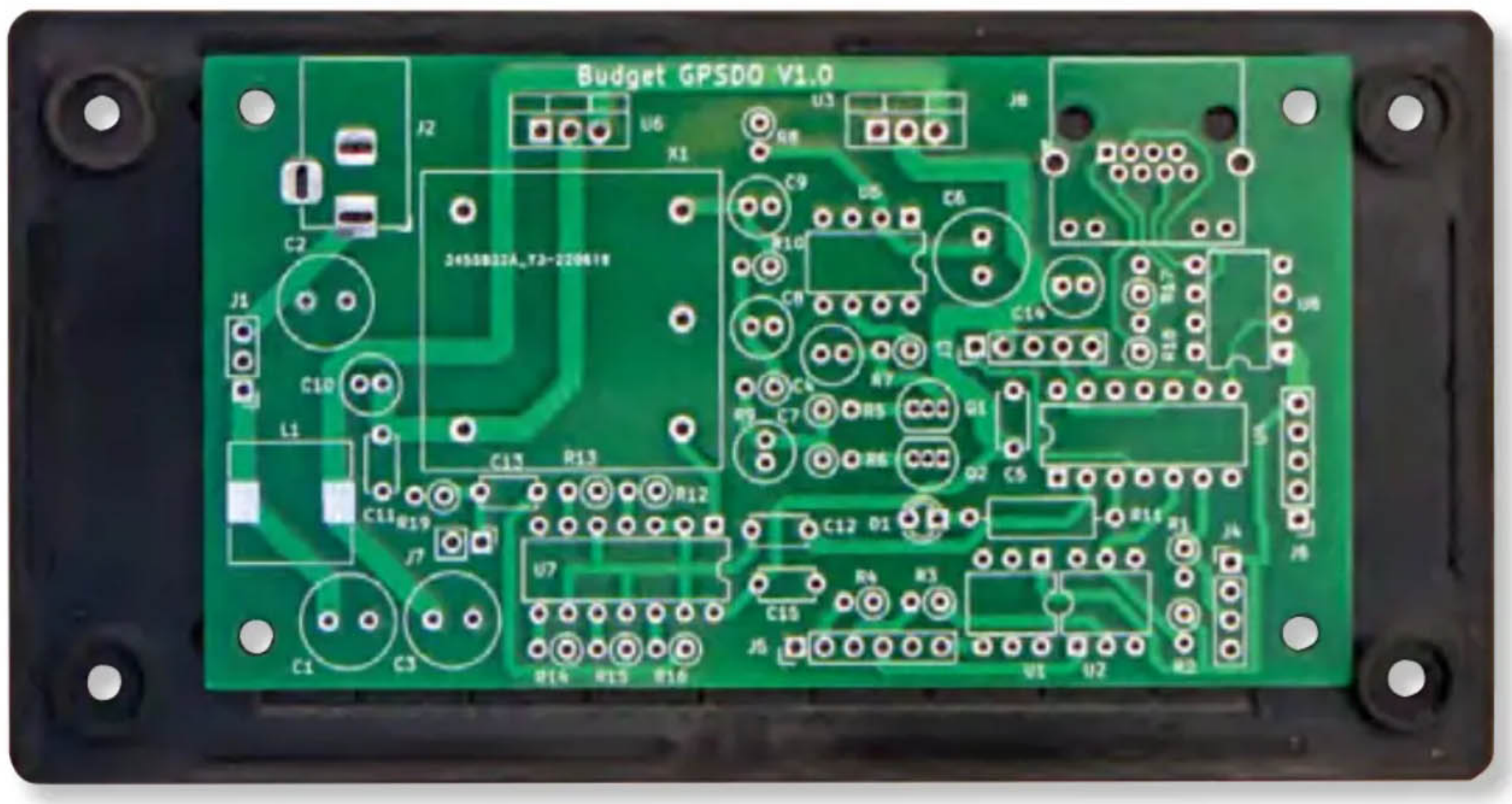


Photo 1: the preferred position for mounting the PCB on a UB3 enclosure.

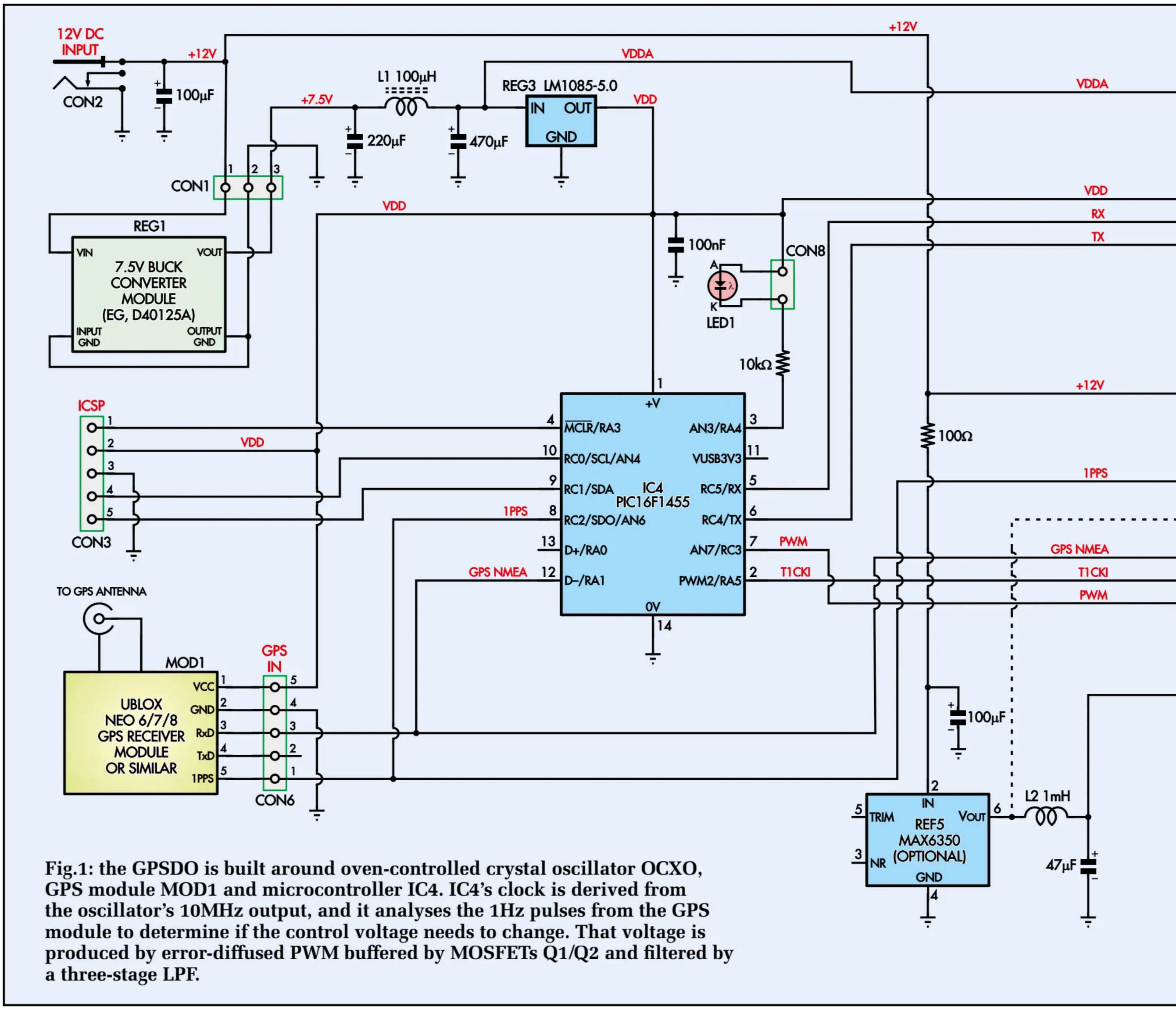

12V DC INPUT
CON2
100µF
+12V
+7.5V
L1 100µH
220µF
470µF
REG3 LM1085-5.0
IN OUT GND
VDD
VDDA
CON1
1 2 3
REG1
7.5V BUCK CONVERTER MODULE (EG, D40125A)
VIN
VOUT
INPUT GND
OUTPUT GND
100nF
CON8
A
K
LED1
10kΩ
RX
TX
100Ω
1PPS
GPS NMEA
T1CKI
PWM
ICSP
CON3
IC4 PIC16F1455
+V
MCLR/RA3
RC0/SCL/AN4
RC1/SDA
RC2/SDO/AN6
D+/RA0
D–/RA1
AN3/RA4
VUSB3V3
RC5/RX
RC4/TX
AN7/RC3
PWM2/RA5
0V
TO GPS ANTENNA
MOD1
UBLOX NEO 6/7/8 GPS RECEIVER MODULE OR SIMILAR
VCC
GND
RxD
TxD
1PPS
GPS IN
CON6
100µF
REF5 MAX6350 (OPTIONAL)
IN
TRIM
NR
VOUT
GND
L2 1mH
47µF

Fig.1: the GPSDO is built around oven-controlled crystal oscillator OCXO, GPS module MOD1 and microcontroller IC4. IC4's clock is derived from the oscillator's 10MHz output, and it analyses the 1Hz pulses from the GPS module to determine if the control voltage needs to change. That voltage is produced by error-diffused PWM buffered by MOSFETs Q1/Q2 and filtered by a three-stage LPF.

A UI is provided to obtain more status information, and some limited control over the GPSDO, via the microcontroller UART. By default, the NMEA data stream from the GPS module is passed through to the UART. Programs are available to decode the information and display items such as the number of satellites in view, their signal strength, position in the sky and the location data's reliability. This can be useful to diagnose performance issues.

The UI can also be accessed by a terminal program such as TeraTerm. The user can change the output from the NMEA stream to a log of what the GPSDO is doing. There are some control functions to change some defaults, reboot or update the software without removing power.

Circuit details

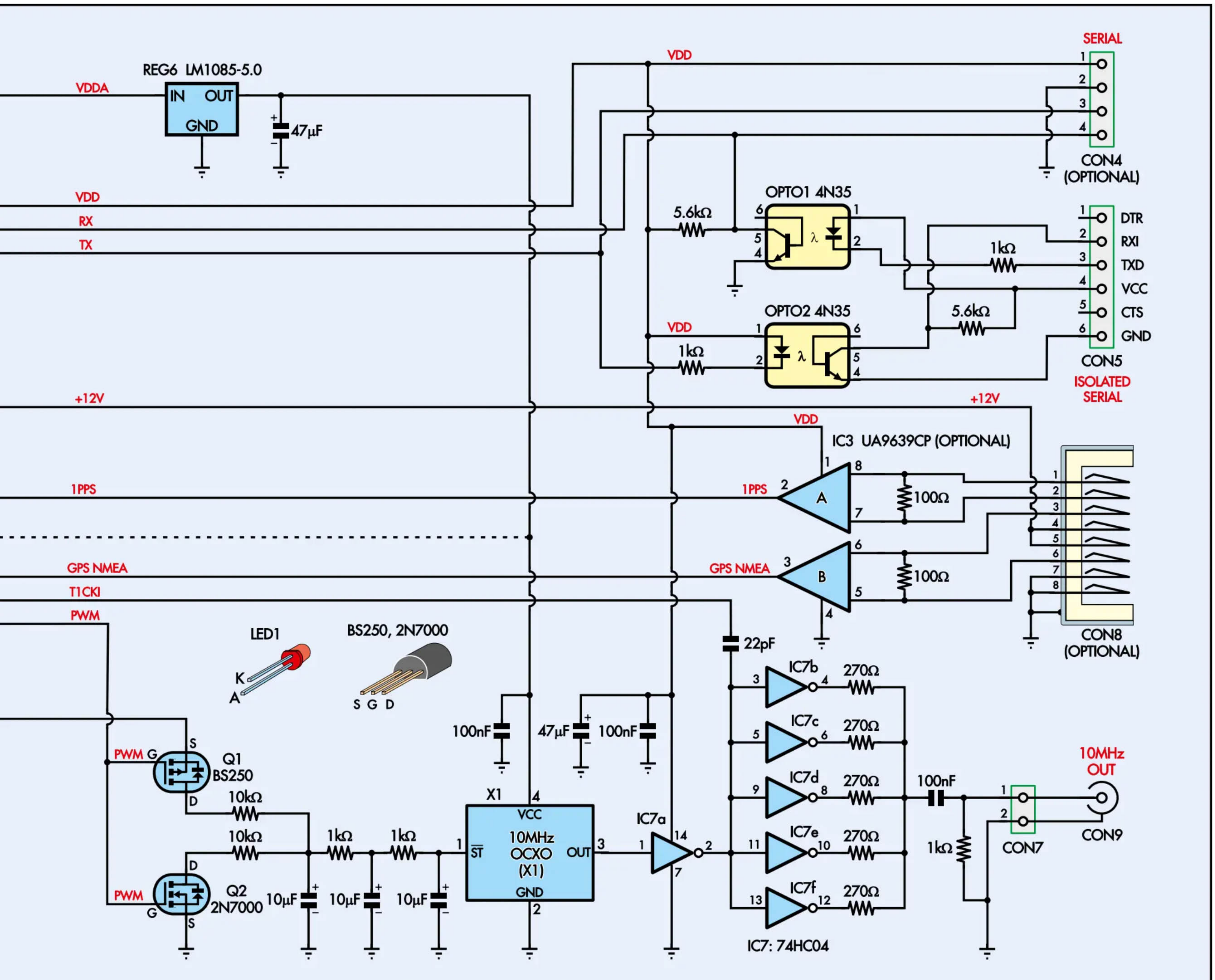
The entire circuit is shown in Fig.1. The controlling PWM signal produced by IC4 emanates from pin 7 and is fed to the gates of P-channel and N-channel MOSFETs Q1 and Q2, which operate as an inverter. When the PWM signal is low, Q1 switches on, pulling the output up via a 10kΩ resistor, whereas when the PWM signal is high, Q2 switches on, pulling the output low via another 10kΩ resistor.

The resulting signal is fed through three RC low-pass filters connected in series to the control terminal (pin 1) of the 10MHz crystal oscillator (OCXO). The time constant of this filter is around one second.

The main reason for inverting the PWM signal with two MOSFETs was so the input to the PWM filter can have its amplitude determined by a very precise reference voltage for stability in the resulting control signal, generated by a MAX6350 voltage reference IC. However, testing showed that it was sufficient to isolate the PWM supply from the general 5V supply. The 5V rail from the standard linear regulator that powers the OCXO is stable enough that the MAX6350 IC is not required.

Therefore, constructors should omit REF5 and instead solder a wire from the output of REG6 to REF5's pad 6 (the dashed line in Fig.1). Regardless of the source of the reference voltage, it is fed through an LC low-pass filter (1mH/47µF) before being applied to the source of MOSFET Q1 to remove any digital noise.

The output signal from the OCXO at pin 3 is fed through an inverter (IC7a) and 22pF AC-coupling capacitor to the clock input pin (pin 2) of microcontroller IC4, which has an internal DC bias. It's also fed to the remaining five inverters in IC7 connected in parallel, with series resistors on the outputs to prevent them from 'fighting' each other if they don't switch simultaneously.


REG6 LM1085-5.0
IN
OUT
GND
VDDA
47μF
VDD
SERIAL
CON4 (OPTIONAL)
VDD
RX
TX
OPTO1 4N35
5.6kΩ
1kΩ
DTR
RXI
TXD
VCC
CTS
GND
OPTO2 4N35
5.6kΩ
VDD
1kΩ
CON5
ISOLATED SERIAL
+12V
+12V
VDD
IC3 UA9639CP (OPTIONAL)
1PPS
1PPS
A
100Ω
GPS NMEA
GPS NMEA
B
100Ω
T1CKI
PWM
CON8 (OPTIONAL)
LED1
K
A
BS250, 2N7000
S G D
22pF
IC7b
270Ω
IC7c
270Ω
IC7d
270Ω
IC7e
270Ω
IC7f
270Ω
IC7: 74HC04
100nF
47μF
100nF
100nF
10MHz OUT
CON9
CON7
1kΩ
PWM
Q1
BS250
10kΩ
10kΩ
1kΩ
1kΩ
X1
VCC
10MHz OCXO (X1)
ST
OUT
GND
IC7a
PWM
Q2
2N7000
10μF
10μF
10μF

Budget GPS-disciplined Oscillator

The output of this set of inverters is AC-coupled to output connectors CON7 and CON9 with a 1kΩ resistor to provide 0V DC bias.

An opto-isolated serial interface is provided at CON5, which can be plugged straight into a USB/serial converter module. By isolating it, we prevent electrical noise from being fed back from a connected computer. Isolation is via two opto-couplers, one for each direction (in/out) – OPTO1 and OPTO2.

Turning now to the circuit's power supply, the incoming 12V is filtered by a 100μF capacitor and then fed into a buck converter module (REG1) that efficiently drops it to 6.5-7.5V. Its output is filtered by a 220μF capacitor, then an LC low-pass filter to remove most of the switching noise (100μH/470μF) before being applied to two 5V low-dropout linear regulators, REG3 and REG6.

REG3 powers microcontroller IC4, hex inverter IC7, the GPS module and some other bits and pieces, while REG6 powers the crystal oscillator and PWM control signal inverter, as mentioned earlier. Both regulators will remove any remaining switching noise from the buck regulator that passes through the LC filter.

The GPS module is wired to CON6. The 1PPS signal is fed to pin 8 of IC4 while the serial stream goes to pin 12.

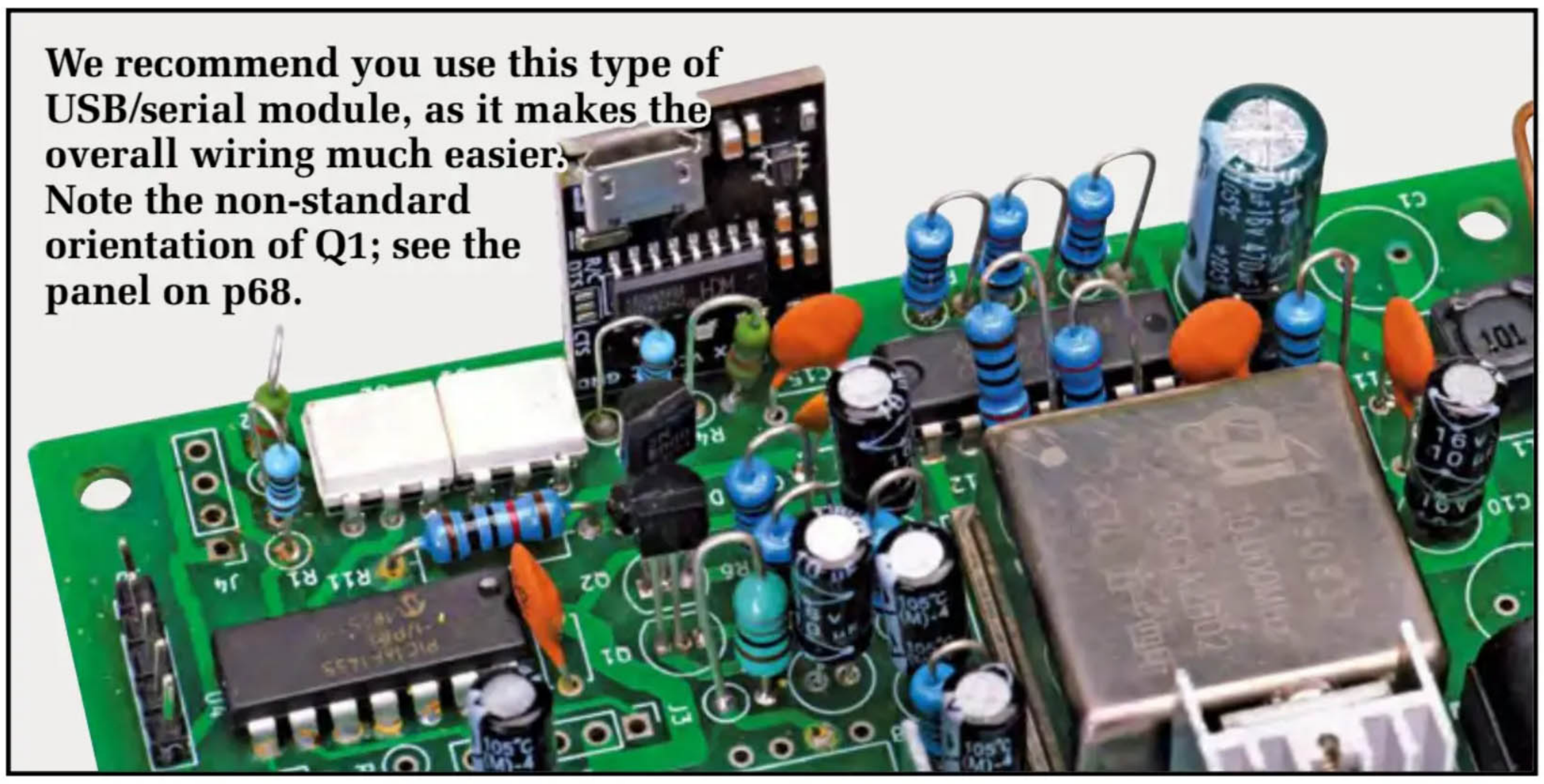
The PCB has provision for data to be fed in from a GPS receiver via dual-differential receiver IC3. This is an experimental interface to allow remote location of the GPS receiver for situations where a local GPS antenna cannot pick up adequate GPS signals. The connection to the remote receiver utilises a standard Ethernet UTP cable, with two pairs for the two signals and the remaining pairs for 12V power.

The remote end requires a buck converter, a line driver and the GPS receiver. This setup has been tested over a 12m cable, and worked over 20m. However, I did not design a PCB for this.

If you wish to implement this, fit the line receiver IC using a socket. For remote use, install the line receiver. For local use, remove the line receiver and plug the GPS receiver into CON6. Otherwise, IC3, CON8 and the two associated 100Ω resistors can be left off.

Preparing the enclosure

Before mounting any parts on the PCB, use it as a drilling template for the mounting holes on the Jiffy box lid, which will become the base. Refer to Photo 1, which shows the preferred position for a UB3 enclosure, with the power connector close to the back and plenty of space for mounting the buck converter module.


We recommend you use this type of USB/serial module, as it makes the overall wiring much easier. Note the non-standard orientation of Q1; see the panel on p68.

Buck converter

We have specified a low-cost 7.5V 1A buck converter that should be a direct fit on the PCB, similar to a standard linear regulator.

The 7.5V option provides plenty of headroom but will increase dissipation in the case (ie, reducing efficiency), although with the small flag heatsinks specified, that should not bother the regulators.

The prototype used an LM2596-based buck converter module with an adjustable output, set to 7.0V (6.5-7.0V is the ideal range). As it has suitable onboard capacitors, the 100µF and 220µF supply capacitors on the main PCB can be omitted. It was attached edge-on using a few pieces of solid copper wire scavenged from an earth conductor; no additional support was necessary (see the photo below). With a UB3 Jiffy box, this converter just fits between the posts in the lid.

You can do something similar, but using the specified regulator is neater and easier, and you don't have to be so concerned with the exact mounting position of the PCB on the lid.

Construction

The project's control PCB is coded 04103231, measures 100 × 55mm and is available frmo the *PE PCB Service*. Refer to the overlay diagram, Fig.2, during construction.

Begin the PCB assembly by fitting the only SMD component, inductor L1. It's reasonably large and easy to handle but requires quite a bit of heat to flow the joints. Turning the iron up will help. First, spread a thin layer of flux paste on the pads and add some solder to one.

Place L1 over its pads and use something to clamp it in place while adding solder to the sides of the two pads, one at a time. Once the solder contacts the inductor, it will solidify, and you will have to hold the iron there, continuing to apply heat until it melts again and flows to form a proper joint. When it remelts, feed in some extra solder until you have nice shiny fillets.

With that in place, move on to the through-hole parts, starting with the resistors. All but one are mounted vertically to save space. While doing that, use one of the lead off-cuts to fit the wire link shown in red in Fig.2, bypassing the unused REF5. Follow with the two TO-92 MOSFETs, being careful not to get the different types mixed up, then the ceramic capacitors, which are not polarised.

Next, install the electrolytic capacitors, which need to have the longer positive leads inserted into the pads marked with a + symbol. The striped side of the can indicates the opposite (negative) lead. Then solder the opto-couplers (OPTO1 and OPTO2) plus hex inverter IC7. These components can all be soldered to the board without a socket, but make sure pin 1 is in the right location in each case before soldering.

Now fit microcontroller IC4, you can solder it directly to the board as there is provision for in-circuit programming/reprogramming (ICSP) via CON3, but you might prefer to use a socket to make it easier to replace. If IC4 is programmed before installation, CON3 is not needed because any updates can be made via the UI on the serial port.

Next, install the linear regulators (REG3 and REG6) plus the buck regulator module (REG1), making sure they are oriented as shown in Fig.2. For REG1, various types can be used, and it isn't always obvious which way around they should go. Check the module and verify that the input and output pins match the 'IN' and 'OUT' labels shown in Fig.2.

After that, fit the OCXO, which can only be inserted into its pads in the correct orientation.

We don't recommend you fit IC3, CON8 or the two resistors next to IC3. Similarly, REF5 should be missing, although you will have already soldered a wire link to its pad 6. You can now fit the DC socket to complete the board.

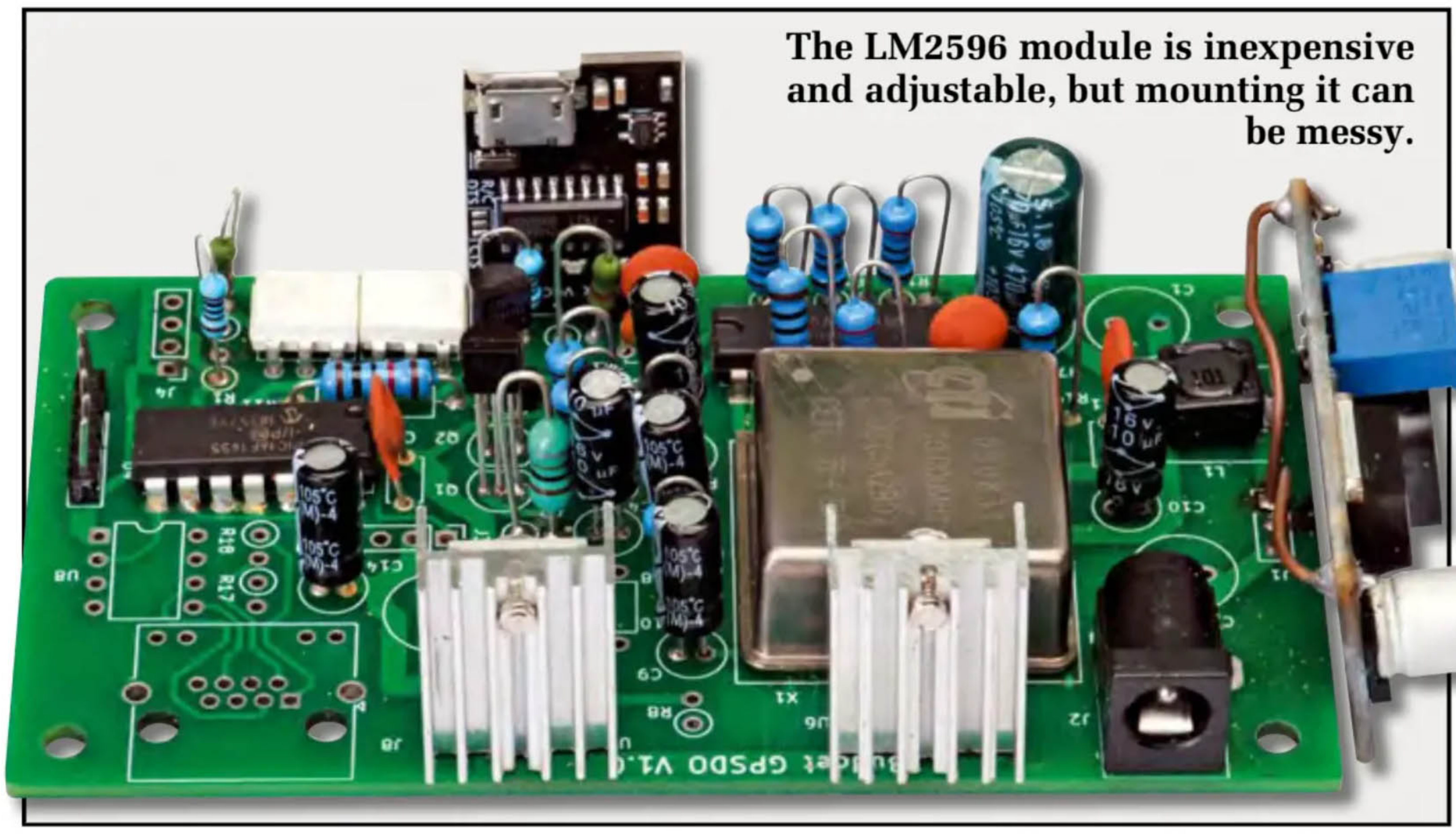
LED1 can be mounted on the PCB, but it is more convenient to fit a two-pin polarised socket in its place and wire up the LED to a matching plug using a length of light-duty figure-8 cable (eg, two wires stripped from ribbon cable). That will let you mount it in a hole in the case later, so it's externally visible.

Similarly, the 10MHz output socket is chassis-mounted and connected via a two-pin header, CON7. It isn't critical that this is a polarised/locking type header; you could use a standard header and DuPont plugs or just solder the wires to the output socket to the pads, although that does make disassembly/testing a bit more difficult.

Fit a standard six-pin header for the isolated USB/serial interface at CON5. The specified USB/serial module has a socket that will plug into this header later. The direct serial interface header, CON4, should not be needed.

Programming the micro

Next, yo need to program your microcontroller. The procedure is


The LM2596 module is inexpensive and adjustable, but mounting it can be messy.

straightforward, just fit CON3 and then program it using an in-circuit serial programmer like a PICkit 3/4 or a Snap.

The PICkit 3 or 4 can supply power to the board during programming. For the Snap, arrange for your own 5V supply or temporarily connect a 12V supply to the board to program the chip.

Once the chip has been programmed, you don't need to open the box to access CON3 to reprogram it. This can be done over the serial port using the XMODEM protocol.

Testing

Before applying power, check your soldering for unwanted shorts, especially around the MOSFETs. Also check to ensure the fillets are all shiny and well-formed, all components are in the correct locations and have the right orientations.

If you decided to use an adjustable buck converter, verify that you've set it for approximately 7V output before connecting it to the main PCB. This is not critical as it can be adjusted later, during testing.

The converters used on the prototypes are adjusted by rotating the onboard potentiometer screw anti-clockwise. Nothing happens for much of the rotation, then the voltage reduces over very little travel.

Connect the LED to its header, apply power and check that it lights up or flashes. Check the output voltage from the buck module at either end of inductor L1 relative to 0V (eg, one of the two larger plated holes on either side of unused socket CON8). Verify it's close to the expected voltage (6.5-7.5V). Also measure the outputs of the two 5V regulators at their tabs and verify that they are both close to 5V.

If the LED is not flashing, probe pin 3 of the PIC. It should be switching between 5V and 0V. If it is, you might have the LED connected the wrong way around.

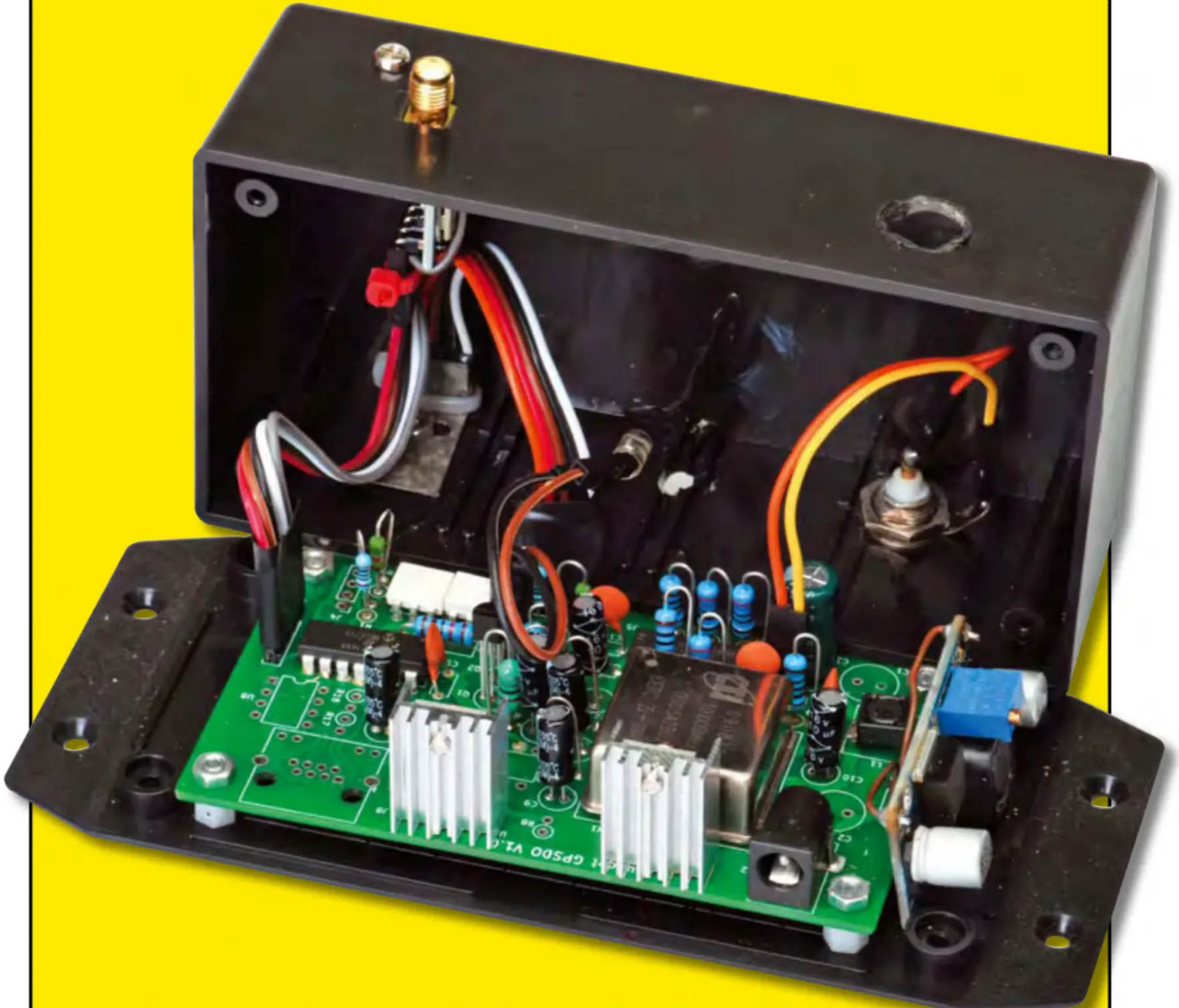
If the LED flashes at 2Hz, the 10MHz signal is not reaching the PIC at its pin 2. Check for a 10MHz signal between the two pins of CON7. It should also be present at pin 1 of IC7 (directly connected to the output of the oscillator).

If all is well, the LED should flash at 1Hz with about 800ms on and 200ms off. This indicates that the PIC is working and using the 10MHz from the oscillator as its clock.

You can check the control voltage at the control pin of the OCXO, which is connected to the right-hand end of the resistor immediately between it and REF5. It should be in the range of 2-3V, most likely close to 2.5V. If that's wrong, it could be due to a problem with MOSFETs Q1 and/or Q2 or a faulty oscillator module.

GPS module wiring

You can now solder the wires from your GPS module to the pads for CON6. Fig.2 shows the wire colours



Once the PCB has been assembled, it needs to be wired to the output socket, GPS module, USB socket and LED1. Note the omitted optional parts.

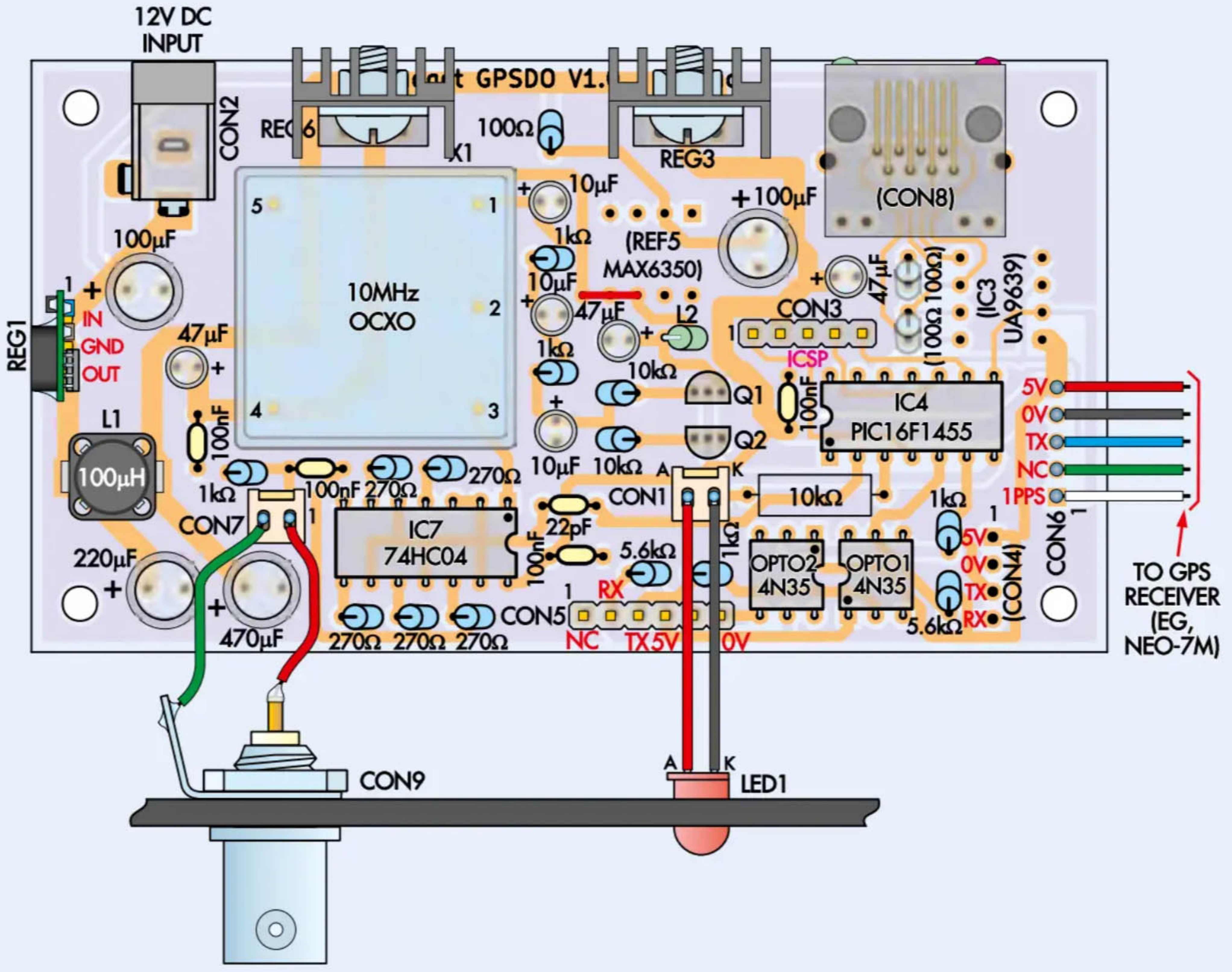
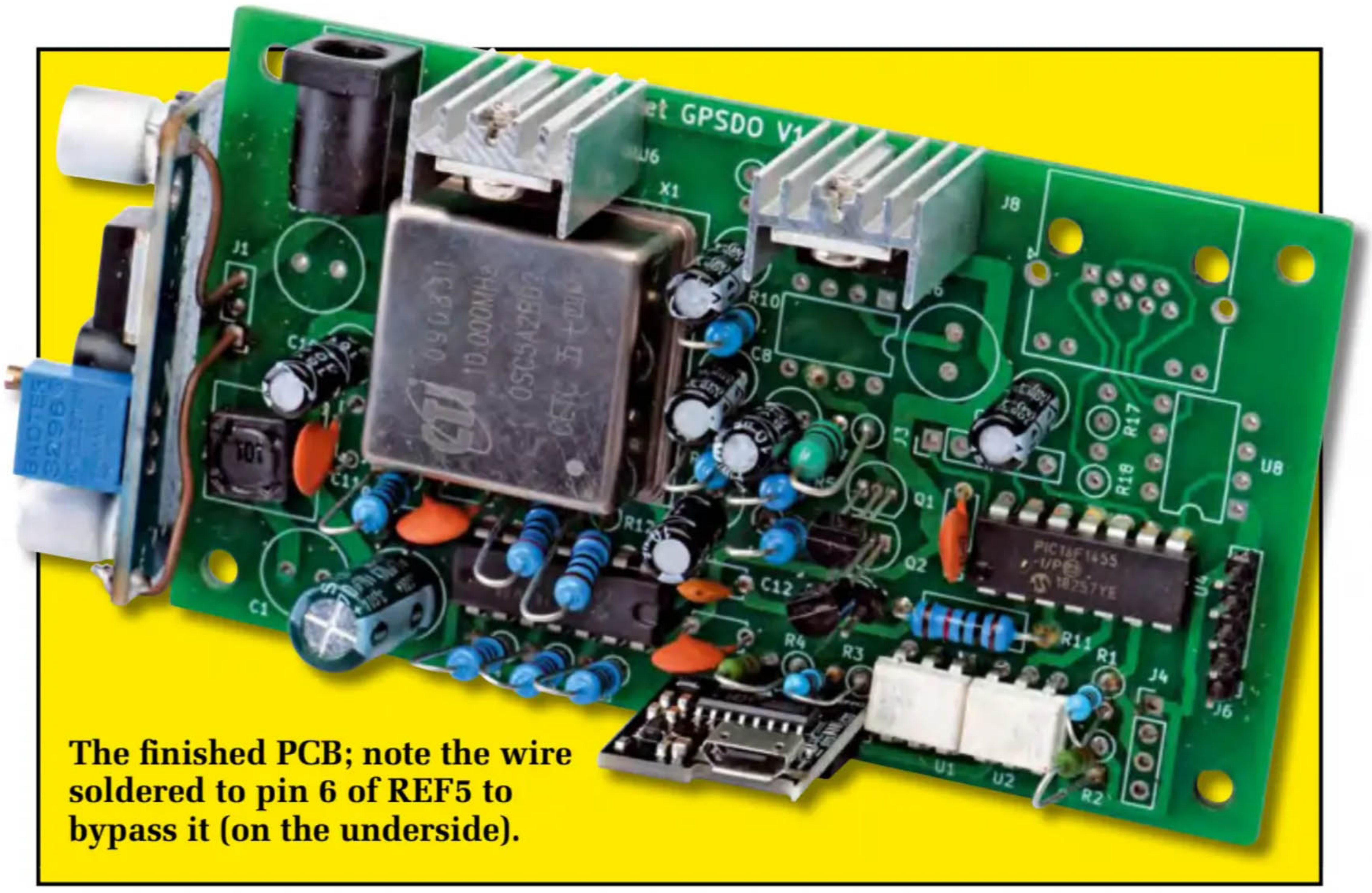

12V DC INPUT
CON2
REG6
100Ω
X1
REG3
GPSDO V1.
10μF
+100μF
(CON8)
5
1
2
3
4
10MHz OCXO
1kΩ
(REF5 MAX6350)
10μF
47μF
L2
CON3
ICSP
47μF
(100Ω 100Ω)
(IC3 UA9639)
100μF
REG1
IN
GND
OUT
47μF
L1
100μH
100nF
1kΩ
100nF 270Ω
270Ω
10μF
10kΩ
Q1
Q2
10kΩ
IC4 PIC16F1455
5V
0V
TX
NC
1PPS
CON6
CON7
A
K
CON1
10kΩ
1kΩ
IC7 74HC04
100nF
22pF
5.6kΩ
1kΩ
OPTO2 4N35
OPTO1 4N35
5.6kΩ
(CON4)
RX
220μF
470μF
270Ω 270Ω 270Ω
CON5
NC
TX5V
0V
TO GPS RECEIVER (EG, NEO-7M)
CON9
LED1

Fig.2: fit the components as shown here, taking care with the orientation of the electrolytic capacitors, ICs, opto-couplers, regulators and LED1. Several parts are not needed and are shown left off, while CON8 and the two 100Ω resistors below it are depicted but not required. Don't forget the short wire link near the middle of the board, shown in red, which bypasses REF5.



The finished PCB; note the wire soldered to pin 6 of REF5 to bypass it (on the underside).

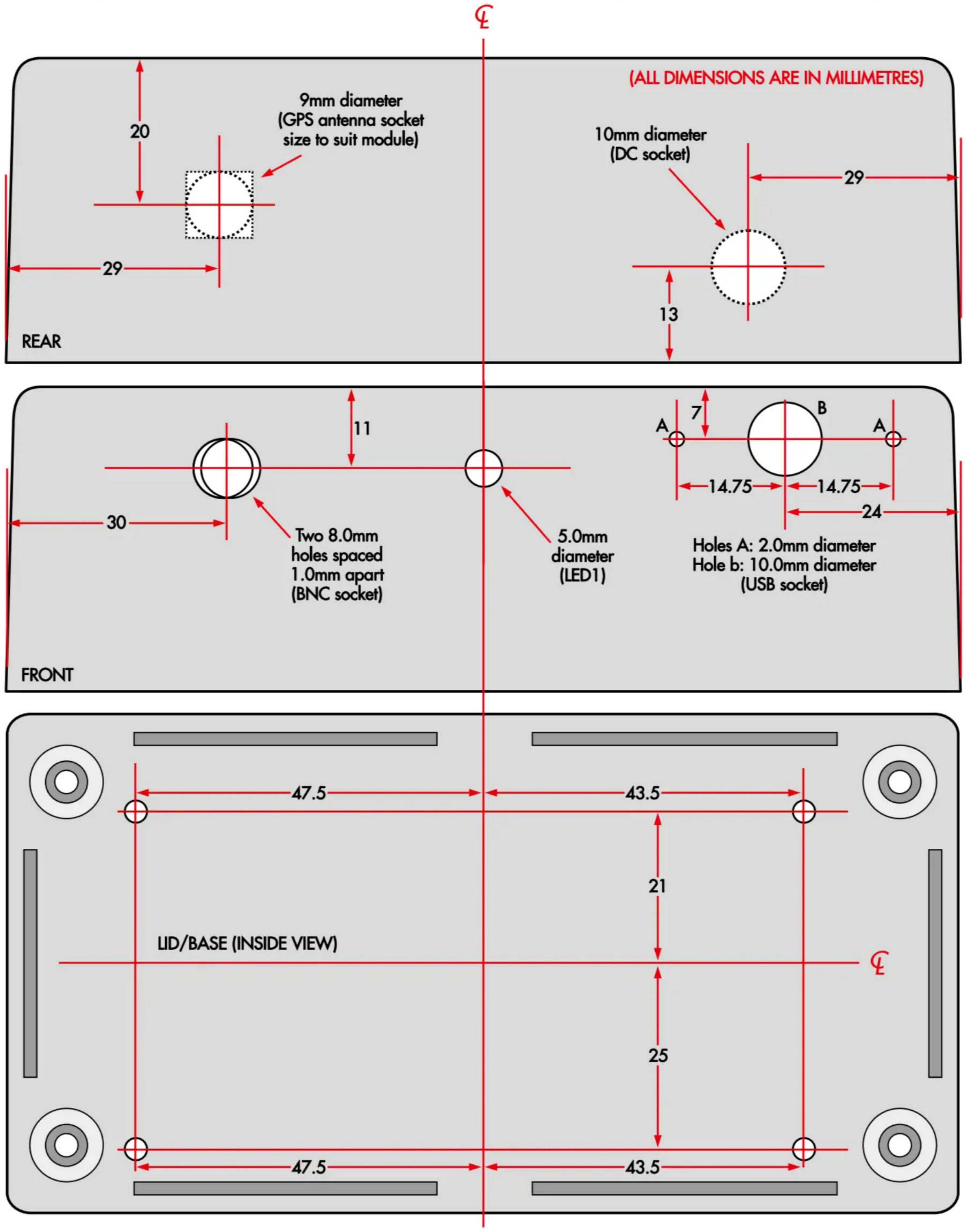
for the suggested Neo-7M module. However, you might decide to use a module with an onboard antenna if you have good signal strength in your lab.

It is best to use an active antenna on a lead as the signal quality indoors is usually too marginal. The antenna is ideally placed outdoors with a good view of the sky. Adequate signal may be obtained indoors near openings such as a window.

If using a different module, consult its data sheet to determine the connections. Most TTL modules should be suitable.

The specified module has a standard 5-pin header, so a short 5-way ribbon cable with DuPont connectors at either end will suffice to connect it to the CON6. In contrast, the VK2828U7G5LF module has an onboard miniature connector and comes with a matching cable with bare ends, so you could solder its wires directly to the board. It also has an enable (EN) wire that needs to connect to the 5V pad.

The system is now ready to be powered up with the GPS module attached. There's a power light on most GPS units; if present, it should light up. If the system LED is now making a double flash at three-second intervals, all is well. That indicates that data is received from the



℄
(ALL DIMENSIONS ARE IN MILLIMETRES)
20
9mm diameter (GPS antenna socket size to suit module)
10mm diameter (DC socket)
29
29
13
REAR
11
7
A
B
A
14.75
14.75
24
30
Two 8.0mm holes spaced 1.0mm apart (BNC socket)
5.0mm diameter (LED1)
Holes A: 2.0mm diameter
Hole b: 10.0mm diameter (USB socket)
FRONT
47.5
43.5
21
LID/BASE (INSIDE VIEW)
℄
25
47.5
43.5

Fig.3: this shows where to drill holes in the lid/base, for mounting the PCB, and in the sides of the case, for the various chassis-mounting connectors. As noted in the text, you should ideally use the PCB as a template to mark the four holes in the lid/base, although you can use this diagram if you've already populated it.

Note: the DC socket and GPS antenna socket locations are only guides, and the actual size and location can vary when it is mounted. So it's best to check them before drilling.

BS250 Pinout

Be aware that there are versions of the BS250 MOSFETs with non-standard pinouts (the standard pinout is DGS left-to-right looking at the flat 'label' side; see Fig.1). If you end up with those, you might need to rotate it or bend the pins. Usually the non-standard versions have their pinout printed on the face.

module but it is not detecting any satellites yet.

Next, plug the USB/serial module into CON5; make sure it's the right way around, with its DTR pin to pin 1 on the left and its GND pin on the right. Connect it to your computer, open a serial terminal on the COM port that appears, power up the board, and you should see one line of text when it detects that it is running with the 10MHz clock.

With the GPS module attached, it should pass through the NMEA data to the serial output (this is the default when first powered up, but you can change it later).

Place the GPS antenna where it will receive a good signal from the satellites. Turn the system on, and the double flash at three-second intervals should resume. It could take up to 30 minutes or possibly a little longer for the GPS module to pick up all the satellites after a 'cold start'. When that happens, the LED flash pattern should change.

The LED reports the number of satellites seen (in binary) until a fix is obtained. This may take some time, sometimes as long as 15 minutes. If the system stays in the double-flash state, the antenna may not be in a good position, or it isn't working.

Final testing

If the GPS module is locating satellites, the system should transition after some time to a flash pattern every four seconds. It starts as five flashes, a single followed by four doubles, and counts down. If there is no flashing, it is most likely that the GPS module has reported a good fix, but the 1PPS signal is not getting to the PIC processor.

Do not allow the system to run for more than an hour after this transition. Turn it off, detach the GPS module, and run the system without the GPS for a few hours or overnight. The reason for this is that most crystal oscillators need some time to settle down after unknown handling before being installed.

Calibration

The GPSDO is self-calibrating. The purpose of the calibration is twofold; it determines the actual sensitivity of the crystal oscillator (the control voltage vs frequency relationship) and a reasonable control voltage to use when the system is started.

After the oscillator has been running for a few hours, turn off the system and reattach the GPS module with its antenna. Let the system run until it delivers one flash every second. This will take more than an hour, and if the GPS signal is marginal, it may be longer (or not achieved – in which case you will need to relocate the antenna).

A single flash per second indicates the GPSDO has completed calibration and has reached 10MHz within 1ppb. A double-flash suggests it may not be within specification.

Parts List – GPS-Disciplined Oscillator

1 double-sided PCB coded 04103231, 100 × 55mm
1 12V DC 500mA+ supply with barrel plug
1 UB3 Jiffy box (**optional**)
1 PCB-mount DC socket (CON2; 2.1mm or 2.5mm ID, to suit plugpack)
1 5V GPS module with 1PPS output and SMA antenna socket **[eg, NEO-6M, NEO-7M or NEO-8M; SC6737]** (MOD1)
1 GPS antenna with wired SMA connector **[SC6738]**
1 CTI OSC5A2B02 oven-conditioned crystal oscillator module (X1) **[eBay www.ebay.com.au/itm/332389156868]**
1 12V input, 7.5V 1A output three-pin buck converter module (REG1) (A good, inexpensive variable voltage output device is **www.aliexpress.com/item/1005002168374063.html**)
1 WeMos style CH340G-based USB/serial module with header socket for serial and micro-USB socket (MOD3) **[SC6736; AliExpress siliconchip.au/link/abjn]**
1 10cm panel-mount micro-USB socket to micro-USB plug (for MOD3) **[SC6736]**
1 10×10mm 100μH 1A+ SMD inductor (L1) **[ASPI-8040S-101M-T or NR10050T101M]**
1 1mH axial RF inductor (L2)
1 5-pin header (CON3; **optional**, for programming IC4 in circuit)
1 4-pin header (CON4; **optional**, for non-isolated serial)
1 6-pin header (CON5; for isolated serial)
2 2-pin polarised headers and matching plugs (CON7, CON8)
1 panel-mount BNC socket (CON9)
1 100mm 5-way female-to-female DuPont cable (CON6; NEO GPS module)
2 flag heatsinks for TO-220 devices **[eBay 182609295159]**
6 M3 × 8-10mm panhead machine screws
4 M3 x 5mm tapped Nylon spacers
2 M3 shakeproof washers
6 M3 hex nuts
2 M2 × 10mm panhead machine screws and hex nuts (to mount USB socket)
1 200mm length of twin-core light-duty figure-8 cable (eg, stripped from ribbon cable)

Semiconductors
2 4N25 or 4N35 opto-isolators (OPTO1, OPTO2)
1 UA9639CP dual differential receiver IC (IC3; **optional**)
1 PIC16F1455-I/P 8-bit microcontroller programmed with 0410323A.HEX, DIP-14 (IC4)
1 74HC04 hex inverter IC, DIP-14 (IC7)
2 LM1085-5.0 low-dropout 5V linear regulators (REG3, REG6)
1 BS250 P-channel MOSFET, TO-92 (Q1)
1 2N7000 N-channel MOSFET, TO-92 (Q2)
1 3mm LED (any colour)

Capacitors
1 470μF 10V radial electrolytic
1 220μF 10V radial electrolytic
2 100μF 16V radial electrolytic
3 47μF 50V radial electrolytic
3 10μF 50V radial electrolytic
4 100nF 50V MKT or multi-layer ceramic
1 22pF 50V NP0/C0G ceramic

Resistors *(all ¼W 1% axial metal film)*
3 10kΩ 2 5.6kΩ 5 1kΩ 5 270Ω 3 100Ω
– two of the 100Ω resistors are optional (used only when IC3 is installed)

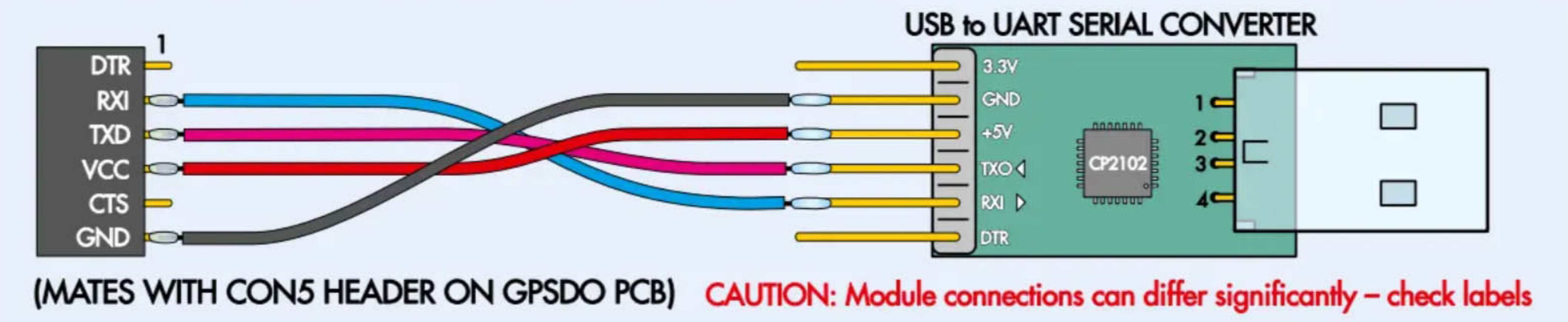

1
DTR
RXI
TXD
VCC
CTS
GND
USB to UART SERIAL CONVERTER
3.3V
GND
+5V
TXO
RXI
DTR
CP2102
1
2
3
4
(MATES WITH CON5 HEADER ON GPSDO PCB)
CAUTION: Module connections can differ significantly – check labels

Fig.4: we're recommending a USB/serial module with a micro-USB socket that plugs directly into CON5 (it has an onboard header socket). However, you can use most USB/serial adaptor you want, including the very common type shown here, wired to a 6-way female header to match CON5.

It is normal to see an occasional period of double flashing, for a few minutes every few hours. This is due to the GPS switching satellites and not having a good fix immediately. A well-positioned antenna will reduce or eliminate these deviations.

After the GPSDO has been switched off, it will take some time to settle down the next time it is turned on. Usually, it is unusable for up to five minutes and reliable after 15 minutes.

For best results, the system should be allowed to run continuously. It improves noticeably for the first week of running. If the antenna is well-positioned, the system should then single-flash (indicating a precision better than 1ppb) and rarely, if ever, double-flash.

Completion

Once you've verified that it's working, all that's left is to finish mounting it in the case. Mount it on the base by inserting 8-10mm-long machine screws from the outside, into 5mm spacers. Drop the PCB on the screw shafts, then use a set of nuts to hold it in place.

Check that the DC socket will line up with the location of the hole shown in Fig.3, then make it. If it's too low or high, you can adjust either the hole's location or the size of the spacer between the PCB and the lid. Make the other required holes, too; if your arrangements differ from what we've suggested, you might need to adjust some of the hole positions and sizes.

If your GPS module has an onboard antenna, you can attach it to the inside of the case using double-sided tape. Otherwise, drill the hole for the antenna connector and mount the GPS module to that hole. You will probably need to use neutral-cure silicone sealant to glue it inside the case as the SMA socket does not have a retaining nut; the threads are only for the SMA plug.

Various approaches can be used for the USB interface. On the prototypes, we wired up a low-cost USB/serial adaptor, as shown in Fig.4, then wired it up to a chassis-mounting 'extension cable' style USB socket. However, we think we've come up with an easier and neater solution for the final version.

The USB/serial adaptor specified in the parts list plugs directly onto header CON5 (watch the orientation). You will then have a micro-USB socket facing up from the PCB (as shown in the photos). The parts list also specifies a chassis-mount micro-USB socket with a short cable that plugs right into that socket.

That just leaves the output connector. If you haven't crimped and soldered the output connector wire with the polarised plug at one end and BNC socket at the other, do that now, then mount it on the side of the case where it won't interfere with the PCB. Plug it into CON7 and check that the connector shell has continuity to the PCB ground.

Finally, check that everything is working before 'buttoning up' the GPSDO in its case – verify that the LED flashes when power is applied, a ~10MHz signal appears at CON9, and you can establish USB communications via the chassis socket. Make sure the GPS antenna is plugged in and it is ready to use.

The HEX file, source code and documentation for the GPSDO can be downloaded from from the May 2024 page of the *PE* website: **https://bit.ly/pe-downloads** or from the author's GitHub: **https://github.com/ajcashin/budget-gpsdo**

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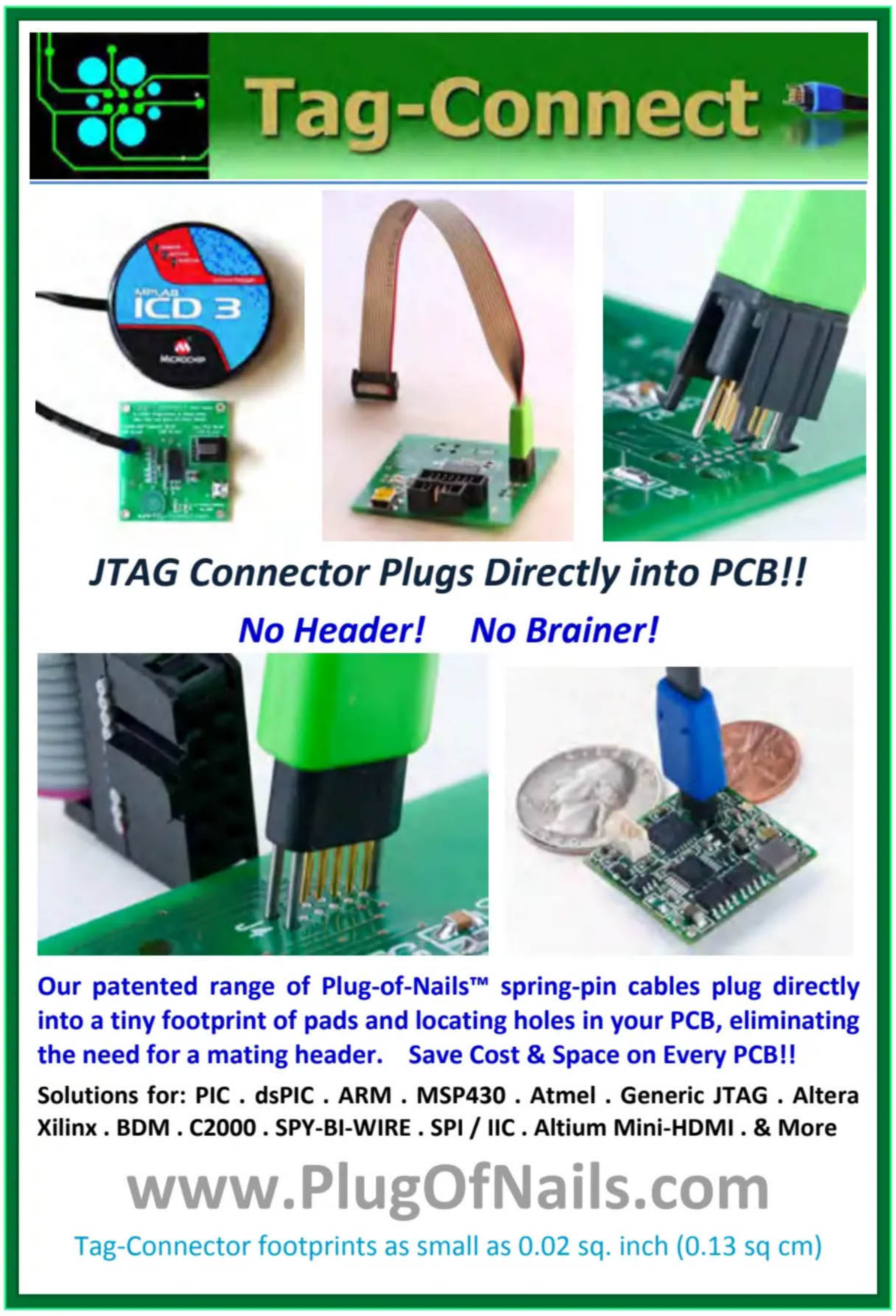

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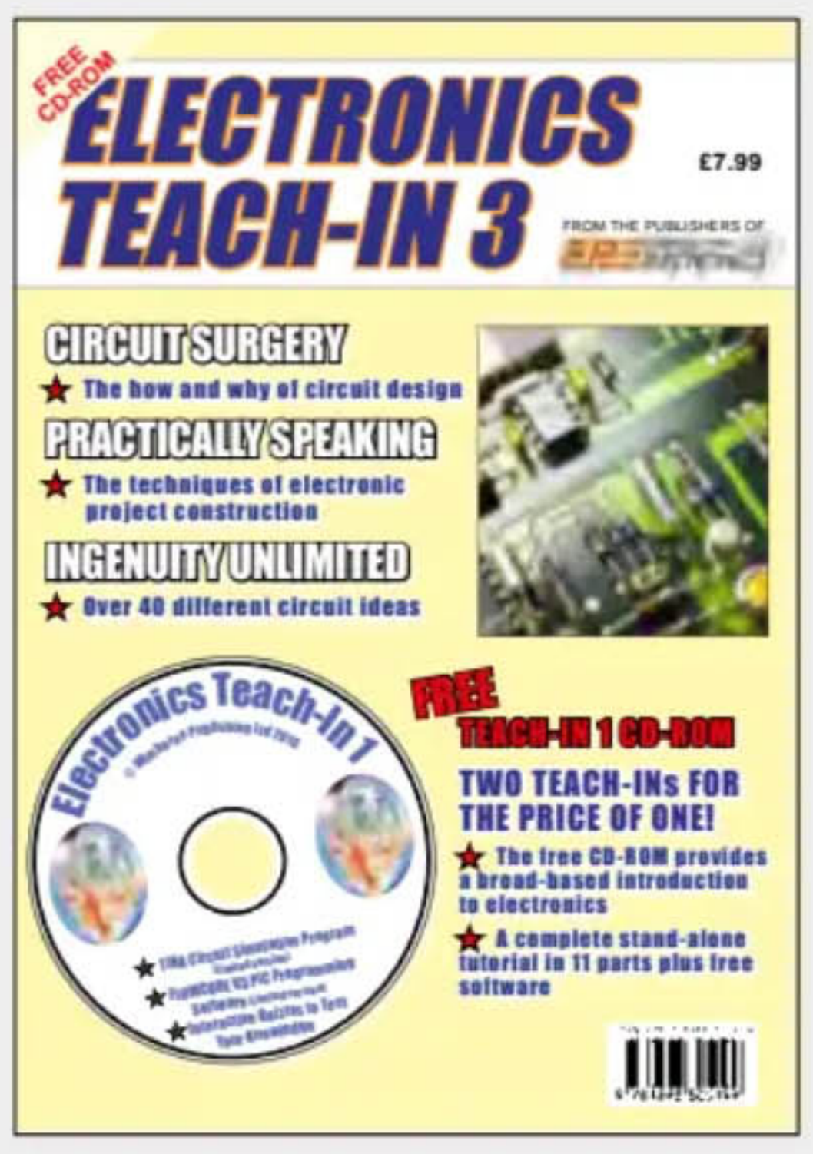

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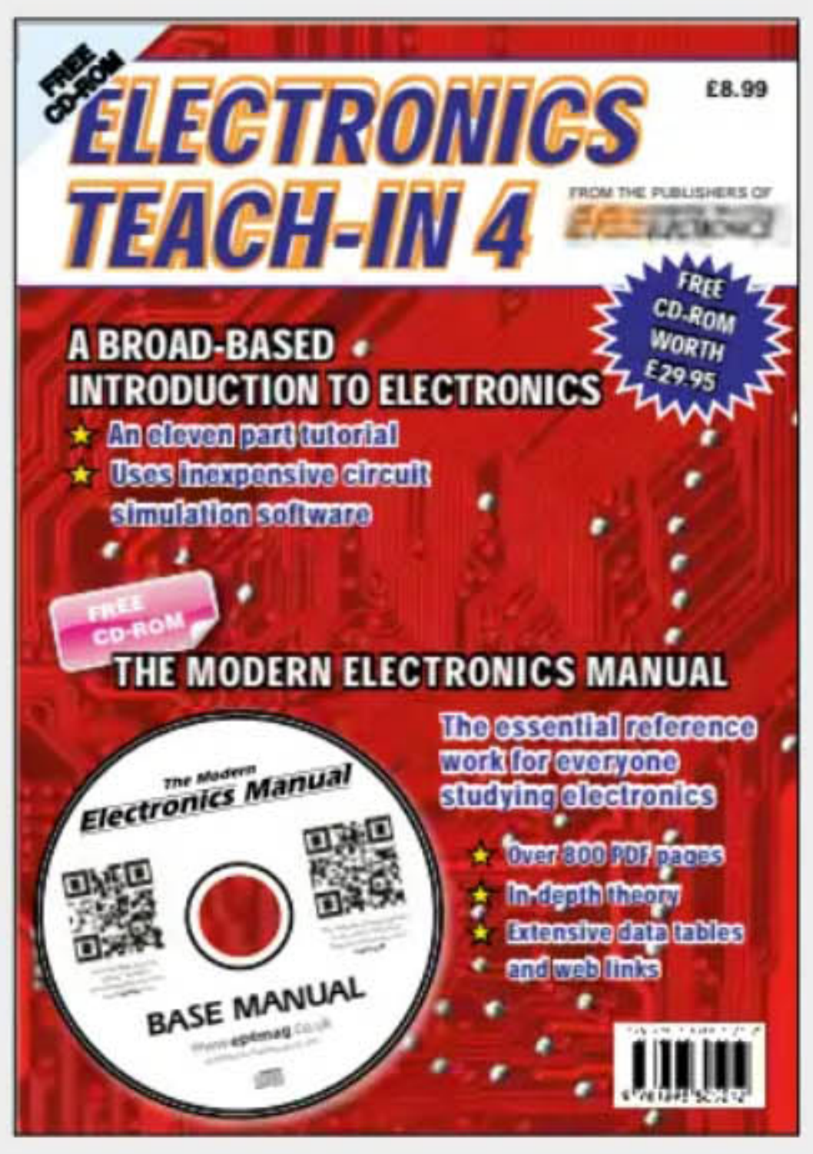
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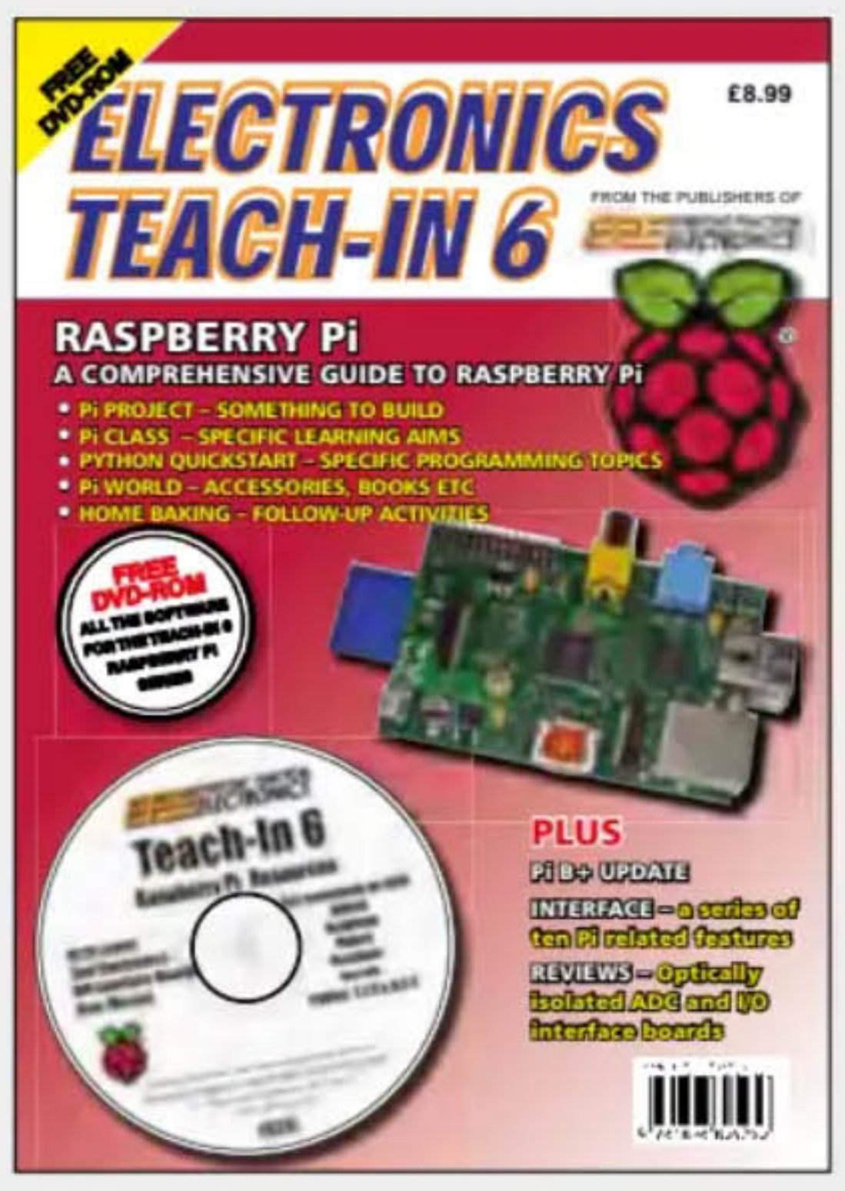

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Dual RF Amplifier for Signal Generators

This small RF amplifier has two outputs with individually selectable gains. This makes it suitable to add to a signal generator to provide a higher output level, or for better drive strength, or 'fanning it out' to multiple other pieces of equipment and more.

by Charles Kosina

CSE220602
C1
R2
R3
C2
R4
R1
C3
C5
C4
RV2
R5
R6
C7
R8
C6
R9
R10
R7

Many signal generators do not provide a high enough output level for certain uses. This small PCB uses an OPA2677 high-speed dual op-amp to boost signals of 100kHz-75MHz at around 0dBm (1mW, 225mV/-13dBV into 50Ω) to around 18dBm (63mW, 1.78V/5dBV into 50Ω).

The OPA2677 has impressive specifications. It can operate on voltages from 3.3V to 12V, has rail-to-rail outputs, a high drive capability and a gain bandwidth (GBW) of 200MHz. But what makes it stand out is a slew rate of 1800V/μs, which means it can provide a large output swing for high-frequency signals.

Since it is a dual op amp, my design provides two outputs for the one input signal. Individual feedback resistors and a potentiometer set the gain for each output.

The maximum gain is 1 + (470Ω ÷ 68Ω) = 7.9 times with the 1kΩ single-turn trimpot set to minimum. The lowest gain is 1 + (470Ω ÷ 1068Ω) = 1.44 times with the trimpot set to maximum. The output impedance is 50Ω and it will safely drive a 50Ω load.

The power supply voltage should ideally be in the range of 9-12V. You could use 5V DC, but the amplified signals will be limited to 5V peak-to-peak at the op amp output and 2.5V peak-to-peak at the 50Ω load, or 884mV RMS (13.9dBm/24mW). The maximum output with a 12V supply is about 25dBm, as shown in the specifications panel.

The *RF Amplifier* is useful from 100kHz to 75MHz, although once past 50MHz, the maximum output level starts to drop off. Table 1 shows spot measurements at several frequencies using my signal generator as an input. The output variability somewhat depends on the signal generator variation in output level.

The OPA2677 is not cheap, about £5 from Digi-Key, Mouser or element14, but I bought five from AliExpress for £8. Still, even if you pay £5 (each), the overall cost of building this *RF Amplifier* is modest.

Circuit description

The whole circuit is shown in Fig.1. The signal fed in via SMA connector CON1 is AC-coupled to both halves of dual op amp IC1 via 100nF capacitors. These signals are biased to half the VCC rail (eg, 2.5V for a 5V supply or 6V for a 12V supply) using 470Ω resistors.

Those coupling capacitors and bias resistors form high-pass filters with a corner frequency of 3.4kHz (1 ÷ [2π × 100nF × 470Ω]) so they will not attenuate signals within the specified operating frequency range, from 100kHz to 75MHz.

The signals are coupled to the non-inverting input pins, so the amplifiers do not invert the signal phase. The outputs of the op amps (pins 1 and 7) are fed back to the inverting inputs (pins 2 and 6) via 470Ω resistors, which form voltage dividers with trimpots VR1/VR2 and their series 68Ω resistors.

The 100nF capacitors in the feedback network reduce the DC gain of these amplifiers to 1x so that the input offset voltages (up to 5.3mV) are not amplified. The corner frequency of the high-pass filter formed is similar to that of the input networks as the component values are the same.

As mentioned earlier, the op amps have very high gain bandwidths (GBW) and slew rates, so they are effective up to high frequencies. Because the gain bandwidth is fixed, the maximum signal frequency drops as you increase the gain. For example, with the GBW of 200MHz, a gain of four times is possible at 50MHz or about three times at 70MHz.

The outputs of the two op amps are coupled to SMA connectors via 100nF capacitors to eliminate the VCC/2 DC bias and fed through 51Ω resistors for impedance matching. You could change them to 75Ω if you need to feed into a 75Ω device.

The VCC/2 rail is formed by a 1.2kΩ/1.2kΩ voltage divider with a 100nF capacitor from the junction to ground to eliminate supply ripple and keep the source impedance low at higher frequencies. Op amp IC1 also has a 100nF supply bypass capacitor.

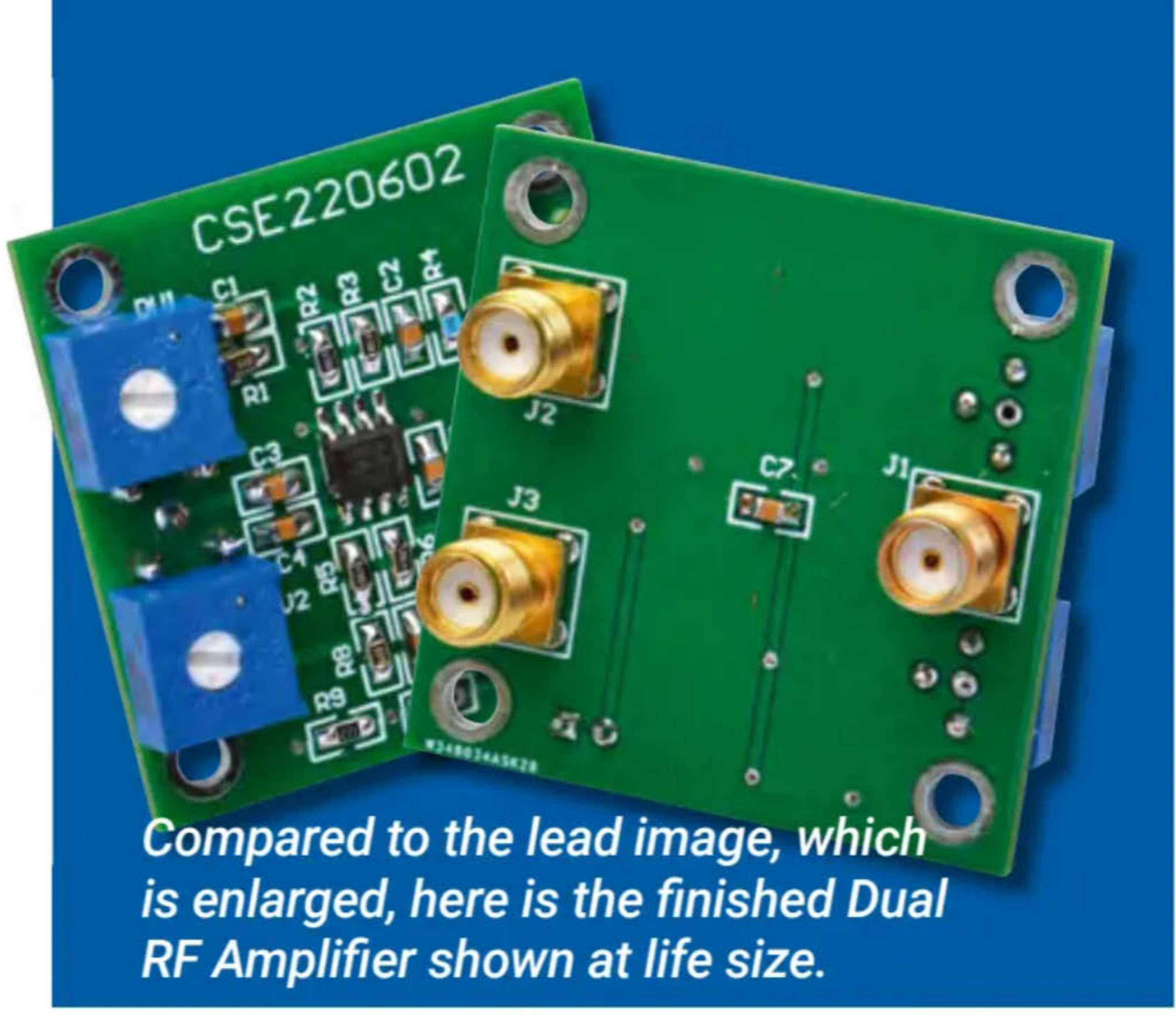
Note that there is no termination resistor for input CON1. You could add an M2012/0805 size resistor (51Ω or 75Ω) across the terminals of the SMA socket if you need one.

Features and Specifications

- Operating frequency range: 100kHz to 75MHz
- Number of inputs: 1
- Number of outputs: 2, individually gain adjustable
- Gain range: 1.44 times (3dB) to 7.9 times (18dB)
- Maximum output level:
  25.6dBm @ 30MHz (360mW into 50Ω, 12.5dBV, 4.25V RMS)
  23.2dBm @ 50MHz (207mW into 50Ω, 10dBV, 3.2V RMS)
  13.5dBm @ 70MHz (22mW into 50Ω, 0.51dBV, 1.06V RMS)
- Power supply: 9-12V DC @ 20-25mA (or 5V DC with reduced maximum output levels)

Table 1 – frequency vs maximum output level @ 12V DC

Frequency	Output (p-p)	Output (RMS)	Output (dBm)	Output (dBV)
1MHz	9.5V	3.36V	23.5	10.5
10MHz	8.4V	2.97V	22.5	9.5
20MHz	10.0V	3.54V	24.0	11.0
30MHz	12.0V	4.24V	25.6	12.5
40MHz	9.6V	3.39V	23.6	10.6
50MHz	9.1V	3.22V	23.2	10.2
60MHz	5.6V	1.98V	18.9	5.9
70MHz	3.0V	1.06V	13.5	0.51


Compared to the lead image, which is enlarged, here is the finished Dual RF Amplifier shown at life size.

Construction

Construction is straightforward as there are only a couple dozen components. The *Dual RF Amplifier* is built on a double-sided PCB coded CSE220602A that measures 38 × 38mm, which is available from the *PE PCB Service*. Refer to the PCB overlay diagrams, Fig.2 and Fig.3, to guide you during assembly.

Start by fitting the SMDs to the component side, with IC1 first. Determine its pin 1 location – look for a dot or divot in one corner, or failing that, a chamfered edge on the pin 1 side. Locate it with pin 1 towards the upper right with the PCB oriented as shown in Fig.2.

Add flux paste to its pads, then tack one pin with solder and check the alignment of the other pins. If they are good, solder the diagonally opposite pin. Otherwise, heat the original solder joint and gently nudge the part until it is in place.

Then solder the remaining pins, refresh the first one and clean up any solder bridges which might have formed between pins with another dab of flux paste and some solder wick.

Clean flux residue off the board with alcohol or a flux cleaner and inspect the solder joints to ensure they are all good. Next, fit the passives (none are polarised), using a similar technique of tacking one side, then adjusting the alignment and after a brief delay to allow the solder to solidify, solder the other side.

The resistors will be marked with codes indicating their values (eg, 122 or 1201 for 1.2kΩ), while the capacitors will not be marked, but they are all the same value (100nF). When all the SMDs are mounted on that side, flip the board over and solder the lone capacitor on the other side.

That just leaves the six through-hole components: two trimpots, the power header and the three SMA sockets. It's best to fit the SMA sockets next, so you have good access to their pins. Push them down fully and solder all five pins, keeping in mind that you may need some extra heat or flux to solder the four outer pins due to their thermal mass.

Finally, mount the two trimpots and the power header. Use single-turn trimpots as multi-turn types likely have too much inductance. You could solder some figure-8 wire directly to the board for power, but a polarised header is more convenient. Its exact orientation doesn't matter as long as you observe the '+' and '–' markings when wiring it up.

Housing it

This board is small, so it can fit into most cases. A metal case is preferred for RF shielding. See the parts list for suggestions and note that the 51 × 51mm diecast cases sold by Jaycar and Altronics are too small to fit the PCB.

Fig.4 shows the hole positions to drill in the lid or base, and the board can then be mounted using the SMA connector nuts.

Drill a hole in the side of the case to fit a chassis-mount barrel socket and wire it up to CON4. Double-check that the positive wire (usually the tip of the barrel socket) goes to the + side of CON4, as the board has no reverse polarity protection.

There isn't a great need for a power switch as you can simply unplug the plugpack from the wall when you aren't using it. Still, if you want to add a power switch, all you have to do is drill a hole in a convenient location,

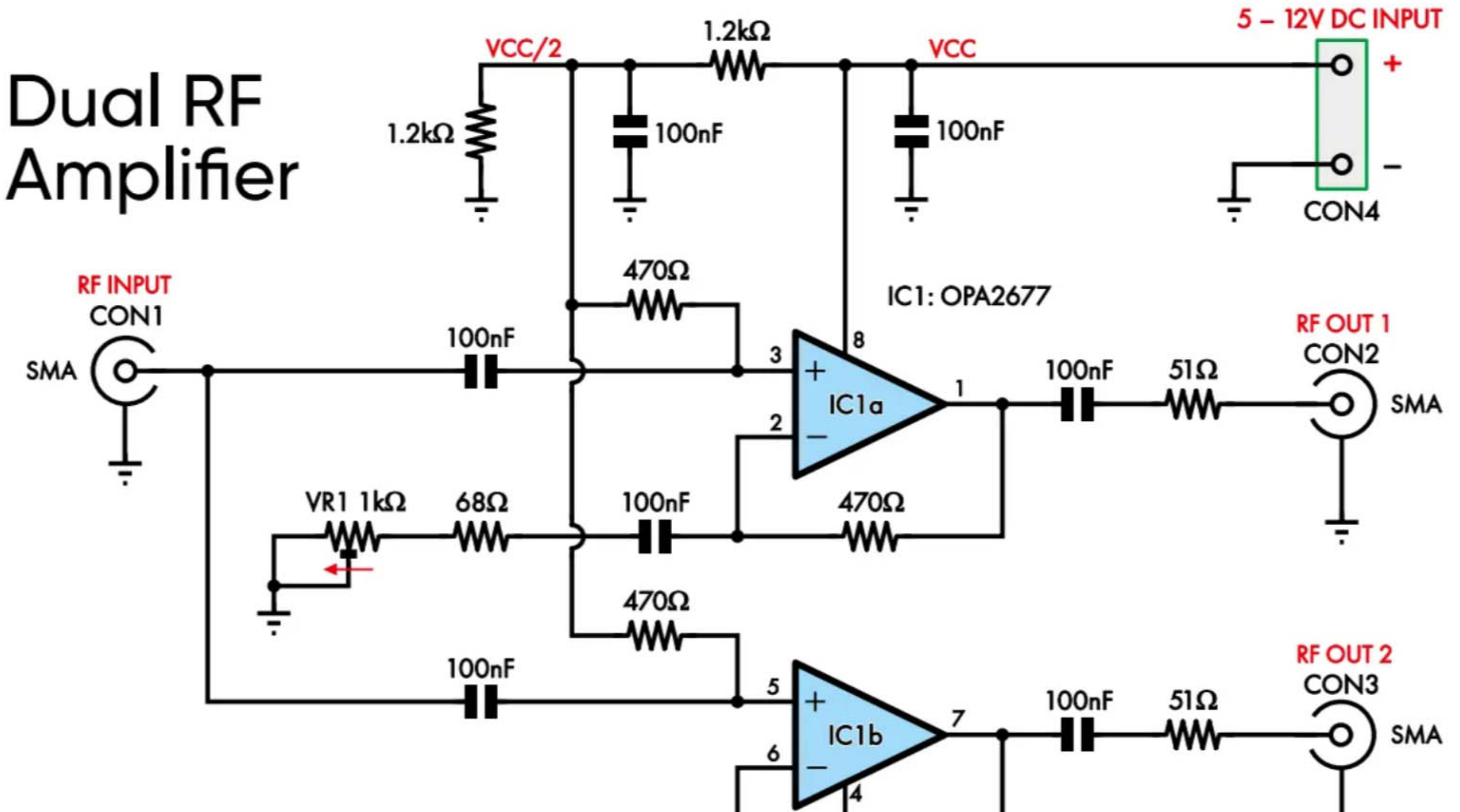
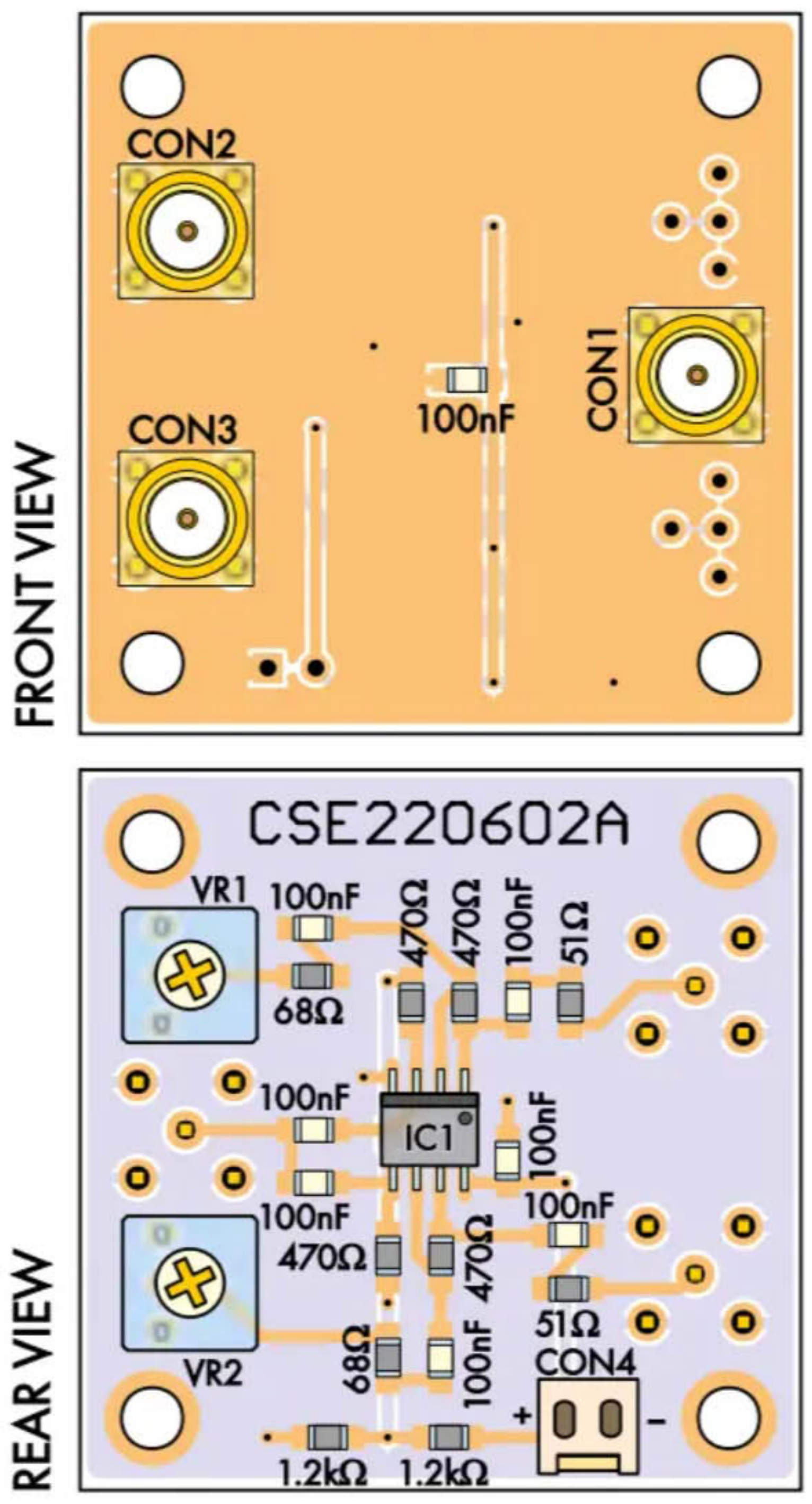


Fig.1: the Dual RF Amplifier is a straightforward implementation of the OPA2677 dual high-bandwidth op amp. Signals are AC-coupled at the inputs and outputs so they can be DC-biased to a half supply rail formed by two resistors and a capacitor. Trimpots VR1 and VR2 adjust the feedback ratio and thus the gain of each individual amplifier.



Figs.2 and 3: most components are SMDs that mount on the rear, while one capacitor and the three SMA connectors are on the front. The RF connector side of the board is covered with a ground plane.

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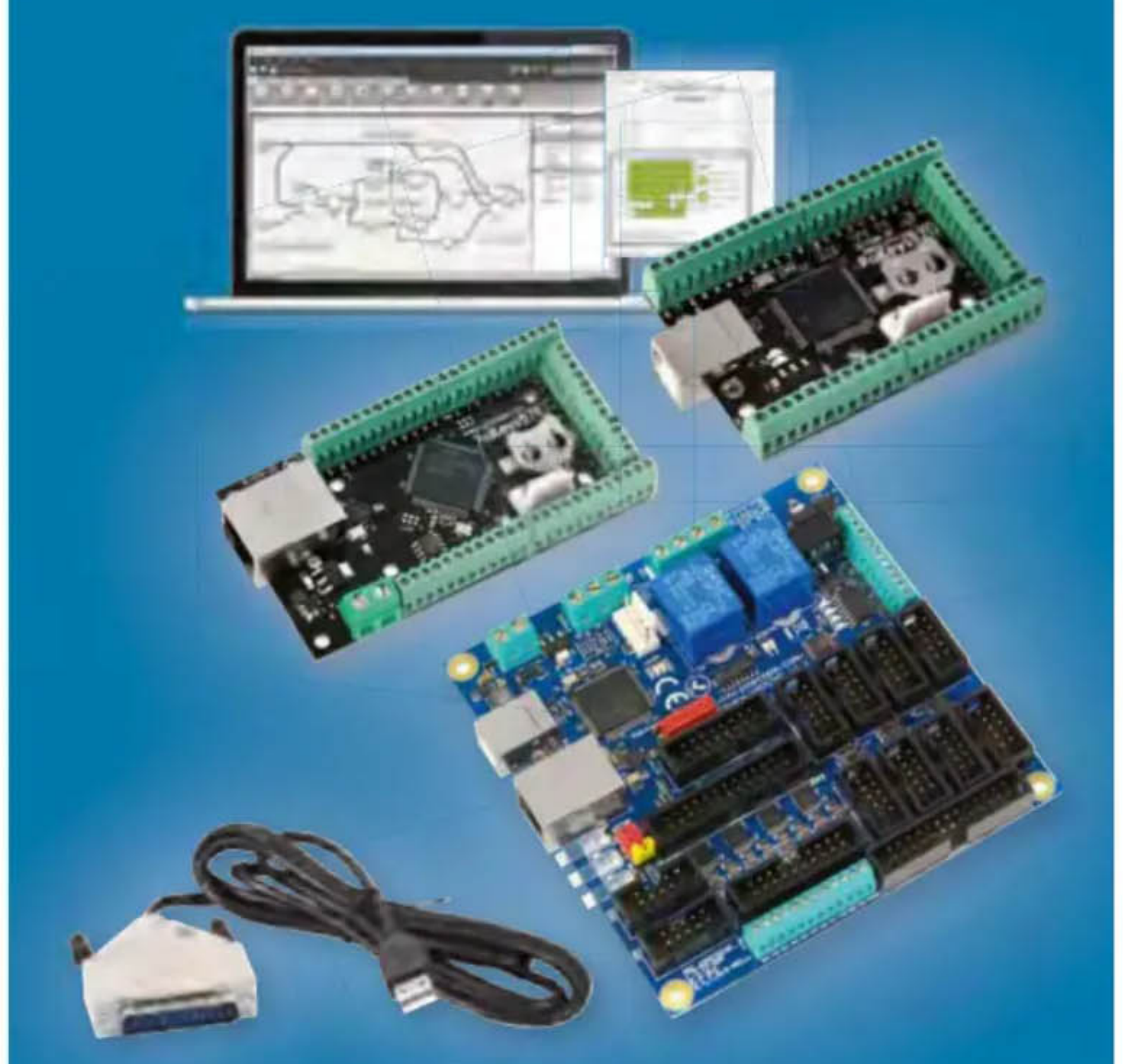
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Parts List – Dual RF Amplifier

1 double-sided PCB coded CSE220602A, 38 × 38mm from the *PE PCB Service*
1 diecast aluminium case, large enough to fit the PCB
  [eg, Jaycar HB5062, 111 × 60 × 30mm]
1 9-12V DC 50mA+ plugpack or other DC supply
1 OPA2677IDDA dual high-bandwidth op amp, SOIC-8
  [element14, Mouser, Digi-Key]
2 1kΩ single-turn 3362P-style top adjust trimpots (VR1, VR2)
8 100nF 50V X7R SMD ceramic capacitors, M2012/0805 size
3 vertical SMA female sockets (CON1-CON3)
1 2-pin polarised header with matching plug and pins (CON4)
1 chassis-mount DC socket to suit plugpack plug
1 short length of light-duty figure-8 cable
1 chassis-mounting SPDT switch (**optional**; power switch)
1 1N5819 schottky diode (**optional**; see text)

Resistors
2 1.2kΩ   4 470Ω   2 68Ω   2 51Ω

mount the power switch and wire it in series with the positive conductor from the barrel socket to CON4.

If you want to add reverse polarity protection, solder a 1N5819 diode to the barrel socket with its anode to the positive tab of the socket, then run the supply wire to the board or switch from its cathode. That will drop the supply voltage slightly, by around 0.3V, so it may have a small impact on the maximum output signal level.

Finally, you might want to drill a couple of small holes in the face of the case opposite the board so that you can slot in a thin adjustment tool to adjust trimpots VR1 and VR2 with the case closed.

That depends on your application; you could just set a different fixed gain for both trimpots and then use whichever output suits your needs at the time.

Before screwing on the lid, unplug the CON4 plug from the board, connect your power supply to the barrel socket and use a DMM to check that the power polarity at the plug is correct. Then plug it in and connect a signal to the input socket.

Verify that an amplified version of the signals appears at the outputs using a scope, signal level meter or frequency counter, depending on what you have on hand.

Using it

There isn't much to it – just power it up, feed in your signal, adjust the level using trimpot VR1 or VR2 if necessary, and take the output from the corresponding socket. The CON2 signal level/gain is adjusted using VR1, and the CON3 signal level/gain is adjusted using VR2.

Keep in mind that VR1 and VR2 are wired such that anti-clockwise rotation increases the gain and clockwise rotation decreases it.

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This article is in memory of Rod Graham, VK3BQJ, who passed away on 4 November 2022.

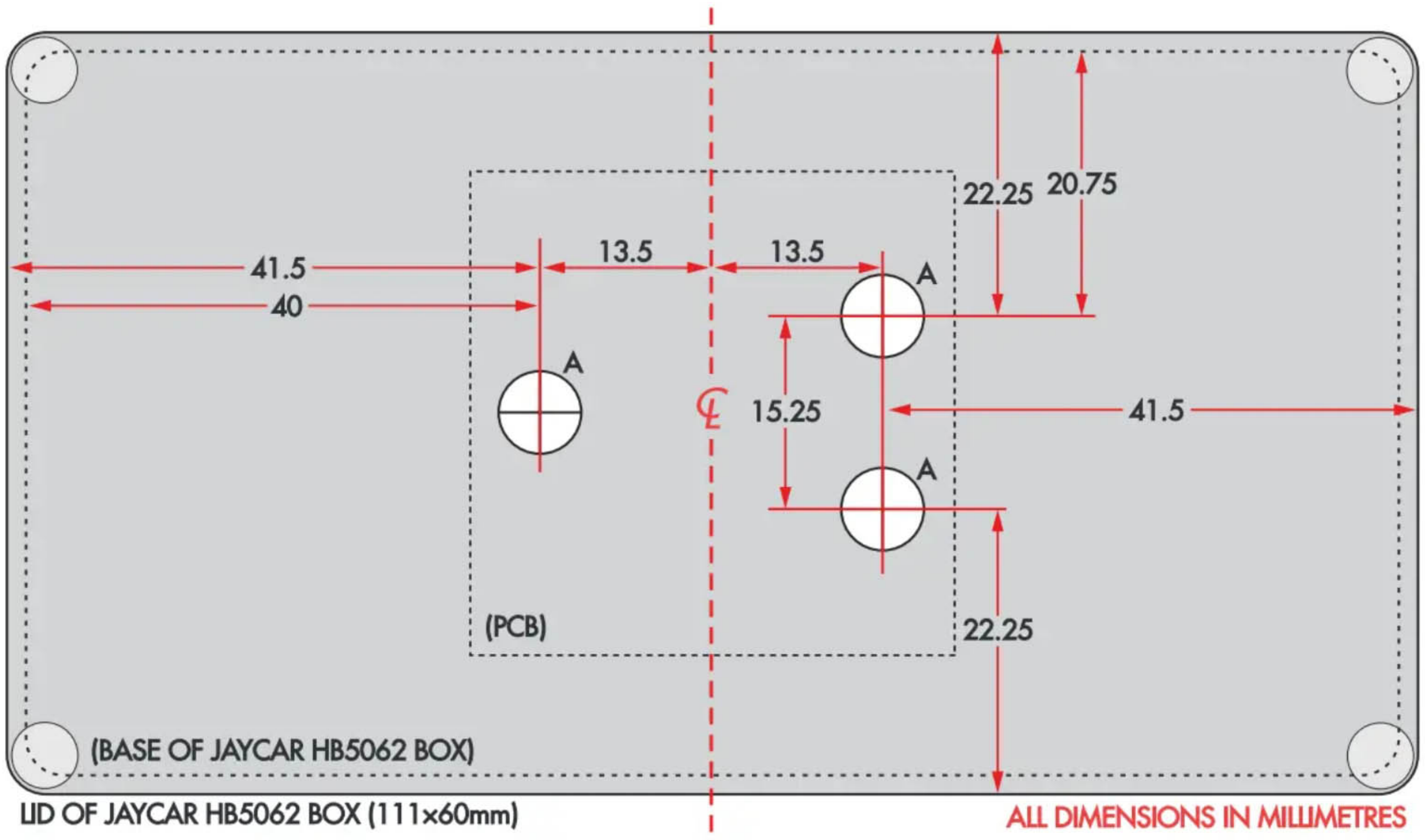

41.5
40
13.5
13.5
A
A
A
℄
15.25
41.5
22.25
20.75
22.25
(PCB)
(BASE OF JAYCAR HB5062 BOX)
LID OF JAYCAR HB5062 BOX (111x60mm)
ALL DIMENSIONS IN MILLIMETRES

Fig.4: just about any metal case would be suitable but this one is relatively compact. The lid is larger than the base, so if using this as a template, cut it to the appropriate outline. The central area could be cut out and transferred to just about any other case. The hole in the side for the power socket is not shown here; it could go just about anywhere.

Using Electronic Modules with Jim Rowe

UVM-30A Module Ultraviolet Light Sensor

This ultraviolet (UV) light-sensing 'breakout' module detects the intensity of UV solar radiation and hence the degree of protection you may need to prevent skin damage. If you connect it to an Arduino or other microcontroller, it can even indicate the current 'UV Index'.

Protection is critical if you spend a lot of time outdoors in the summer sunshine (sunscreen and hat) to avoid sunburn and to lower your chances of developing skin cancer.

The UVM-30A analogue UV light sensing module is ideal for detecting harmful UV rays and can be used to build your own UV sensor. It easily connects to an Arduino or other microcontroller unit (MCU) and with the right firmware, it will indicate the current UV Index or 'UVI'. If you're unsure what this is, please see the 'UV Radiation and UV Index' panel.

Sunburn and skin damage are caused by the UV wavelengths in solar radiation, which can still be quite strong even when the sky is overcast. So checking the UV radiation level is still important.

UV radiation varies in strength during the day, just like visible light and infrared (IR) heat radiation. As with these other wavelengths, its intensity tends to follow a bell-shaped curve, with the peak at the middle of the day or soon thereafter. So it can be worthwhile to keep tabs on the UV radiation level if you are going to be outdoors, even in the early morning or late afternoon.

At the heart of the UVM-30A module is a miniature UV sensor called the GUVA-S12SD. This is in an SMD package measuring 3.5 × 2.8 × 1.8mm and is made by Genicom Co Ltd in South Korea.

Genicom describes their device as a schottky-type gallium-nitride photodiode designed to respond to UV radiation with wavelengths between 240 and 370nm (nanometres). It is also described as being 'blind' to visible light.

The response curve of the GUVA-S12SD sensor is shown in Fig.1. Its sensitivity is very low at wavelengths below 240nm, rising steadily to a peak at 350nm before dropping sharply between 360nm and around 375nm. So it has good sensitivity over the UV-B range from 280nm to 315nm and even better sensitivity over slightly more than half of the UV-A range, from 315nm to 365nm.

The vertical units in Fig.1 are microamps per milliwatt of UV radiation. The Genicom data sheet for the GUVA-S12SD lists the typical peak response of the device as 0.14A/W at 350nm, equivalent to the peak of the curve in Fig.1.

Inside the module

As shown in the circuit diagram (Fig.2) there's very little in the UVM-30A module apart from the GUVA-S12SD sensor (PD1), and a small SGM8521 op amp (IC1) used to convert its output current into a voltage.

The conversion performed by op amp IC1 conforms to the expression $V_O = 4.3 \times 10^6 \times I_{PD}$, where I_{PD} is the current passed by PD1 in amps. So a PD1 current of 280nA should result in an output of 1.2V.

Most of the circuitry in Fig.2 is inside a pale yellow rectangle with a dashed red border because that

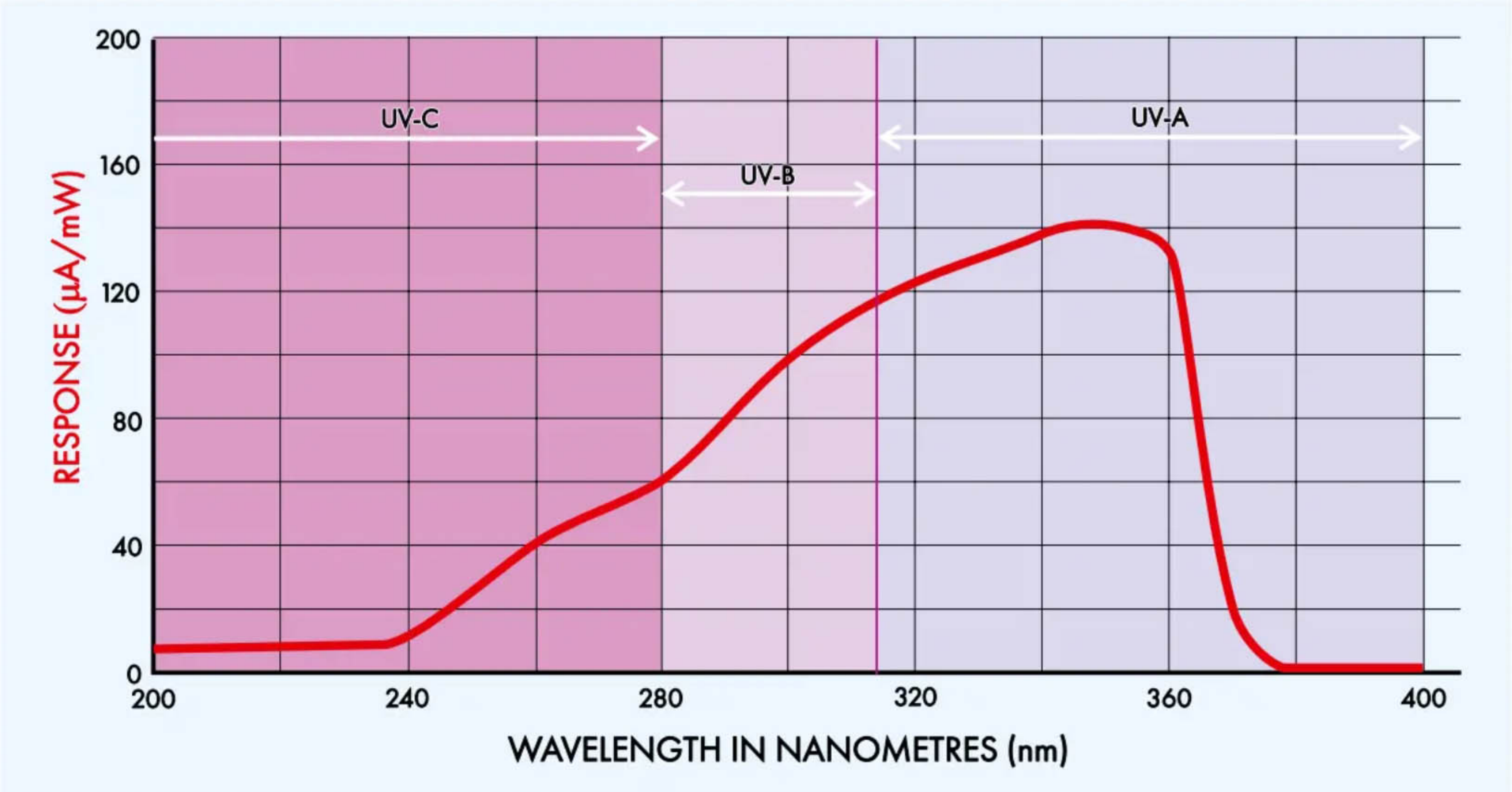


Fig.1: the sensitivity of the GUVA-S12SD sensor to light within the UV spectrum. The x-axis is the light wavelength in nanometres, while the y-axis shows the microamps conducted per milliwatt of incident radiation at that wavelength. This indicates that it's most sensitive to UV-A but will also pick up much of the UV-B spectrum and some UV-C, at reduced sensitivity.

Gsens
UVM30A
out
−
+

The UVM-30A module comprises a larger PCB (28 × 12.5mm) and a smaller PCB (3.5 × 2.8mm). The smaller PCB hosts the GUVA-S12SD UV sensor in a white SMD package.

This image is shown at 250% actual size.

part of the module is on a small sub-PCB mounted on the larger PCB. The smaller PCB measures only 3.5 × 2.7mm square, while the larger module PCB is 28 × 12.5mm. The only components on the larger PCB are a 10µF supply bypass capacitor and a 3-pin SIL header.

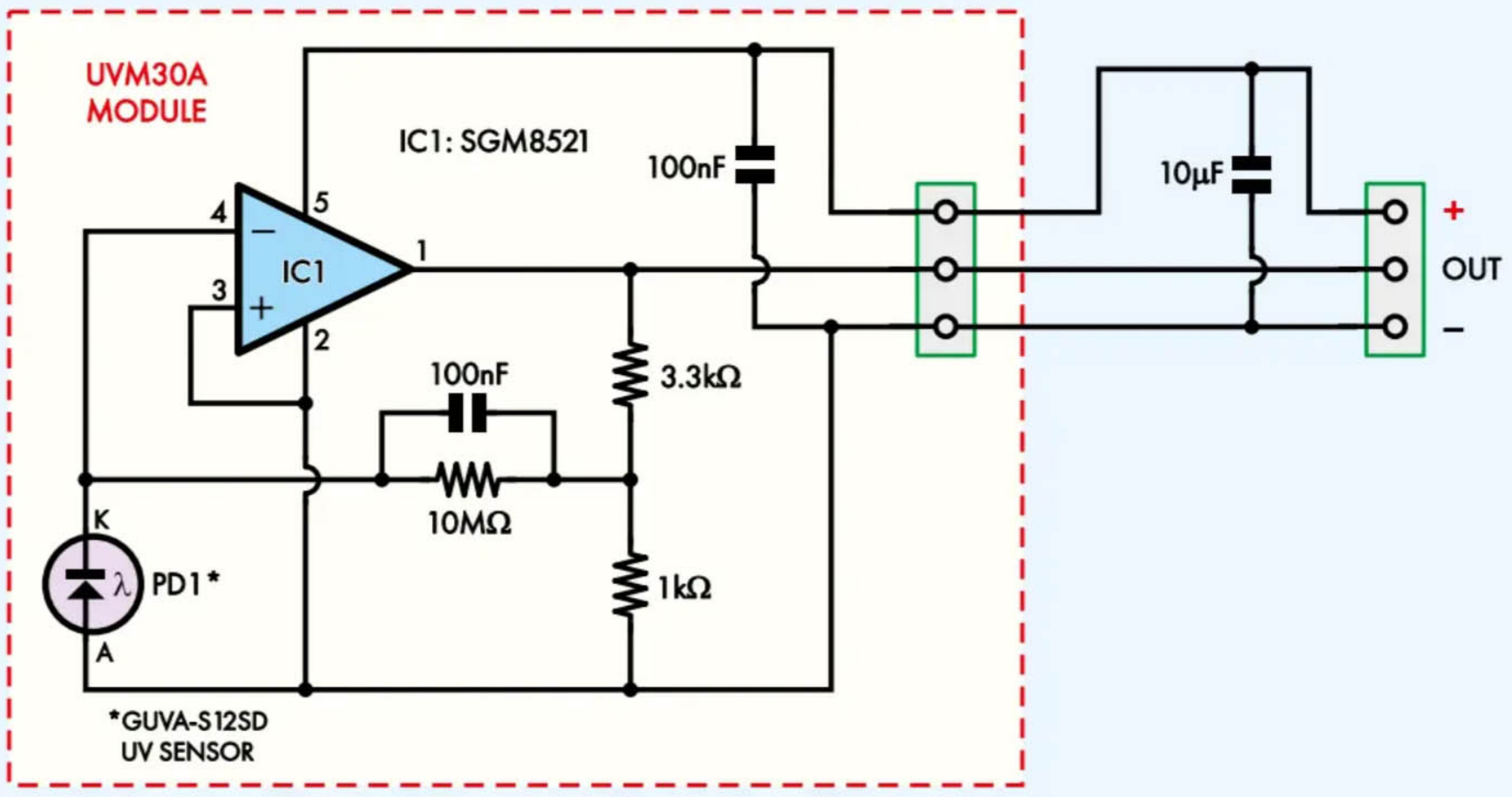

UVM30A
MODULE
IC1: SGM8521
100nF
10µF
4
5
IC1
1
3
2
+
OUT
–
100nF
3.3kΩ
10MΩ
K
λ
PD1*
A
1kΩ
*GUVA-S12SD
UV SENSOR

Fig.2: the circuit of the UV sensor module is pretty straightforward. A bias voltage is applied to the photodiode from the op amp output via a resistor, converting the current into a voltage that's fed to the OUT pin. The yellow box surrounds the components on the sub-PCB; the main PCB just adds a bypass capacitor and the 3-pin SIL header with two power pins (+ and –) and the analogue output.

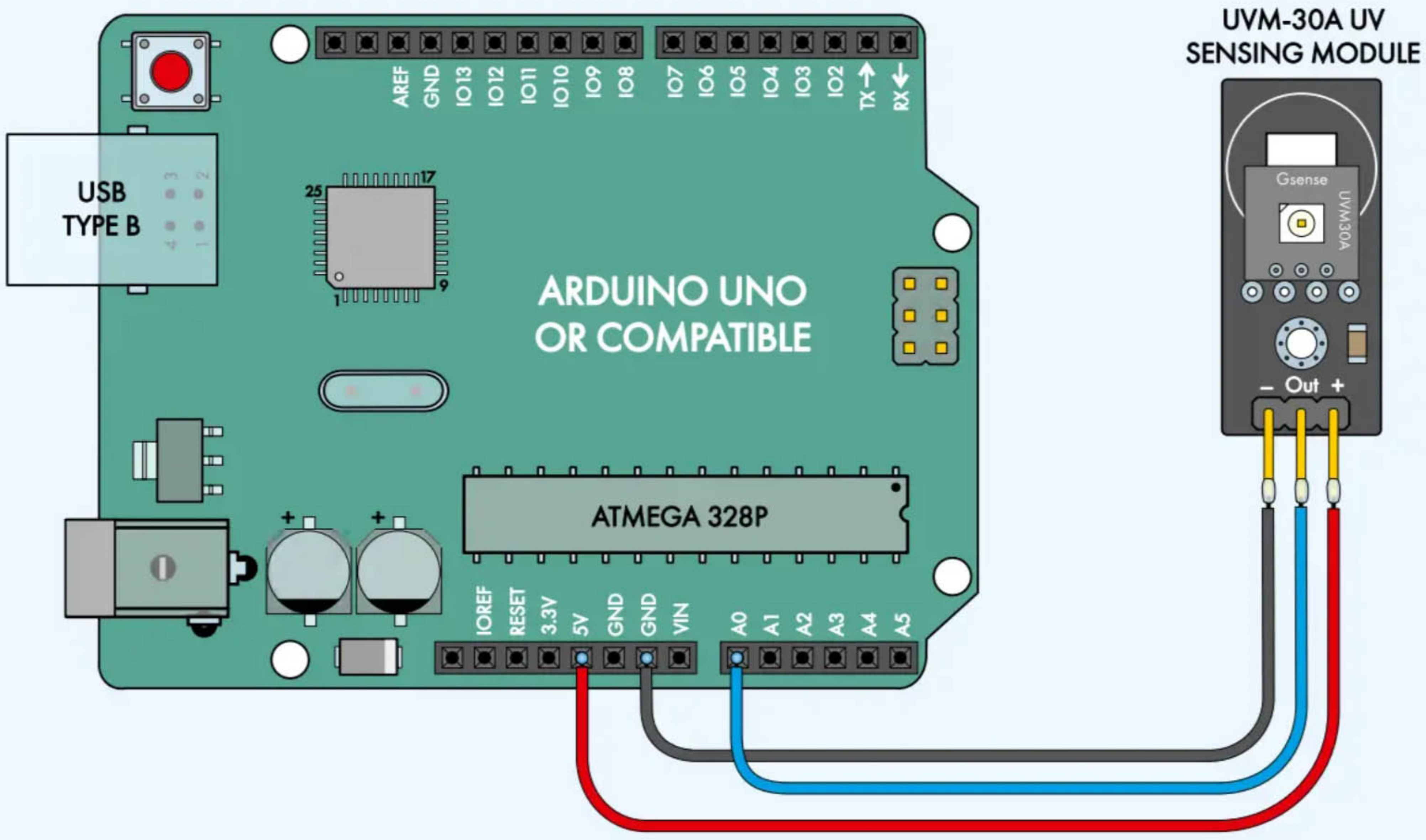

UVM-30A UV
SENSING MODULE
USB
TYPE B
AREF
GND
IO13
IO12
IO11
IO10
IO9
IO8
IO7
IO6
IO5
IO4
IO3
IO2
TX
RX
25
17
9
ARDUINO UNO
OR COMPATIBLE
ATMEGA 328P
IOREF
RESET
3.3V
5V
GND
GND
VIN
A0
A1
A2
A3
A4
A5
Gsense
UVM30A
– Out +

Fig.3: wiring up the module to an Arduino Uno couldn't be much simpler. Just connect the module's + supply pin to its +5V, the module's – supply pin to its GND and the module's output to one of its analogue inputs (in this case, A0, to suit our example sketch).

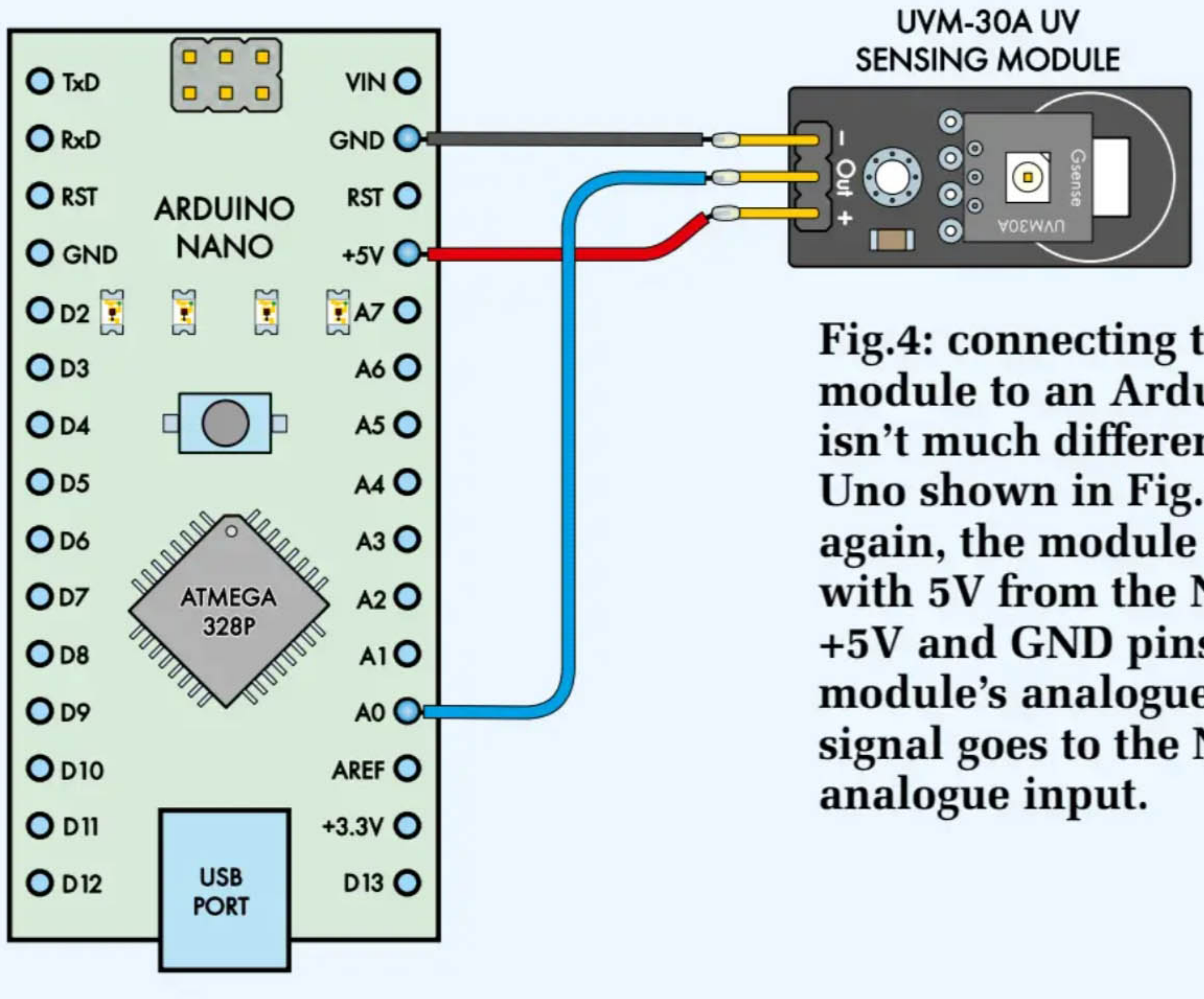

UVM-30A UV
SENSING MODULE
TxD
RxD
RST
GND
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
ARDUINO
NANO
ATMEGA
328P
USB
PORT
VIN
GND
RST
+5V
A7
A6
A5
A4
A3
A2
A1
A0
AREF
+3.3V
D13
– Out +
Gsense
UVM30A

Fig.4: connecting the UV sensor module to an Arduino Nano isn't much different than the Uno shown in Fig.3. Once again, the module is supplied with 5V from the Nano's +5V and GND pins while the module's analogue output signal goes to the Nano's A0 analogue input.

Connecting it to an MCU

Since the module has an analogue voltage output and operates from a DC supply voltage of 3.3V to 5V, it is quite easy to connect to a microcontroller such as an Arduino Uno or Nano. You just need to connect the + and – power pins to the +5V and GND pins on the MCU board, while the 'OUT' pin goes to an analogue input on the MCU, such as the A0 analogue input, as shown in Fig.3 and Fig.4.

Once set up, all that's needed is suitable firmware for your Arduino/MCU. After searching the Internet, I found a website with a graph showing the output voltage of the UVM30A module plotted against the equivalent UV Index (see **https://bit.ly/pe-may24-uv**). I've redrawn this as Fig.5.

On the same website, I also found an Arduino sketch for a UVI sensor, although this sketch was designed to display the calculated UVI level using a Nokia 5110 LCD module.

I adapted this sketch into one that displays both the module's output voltage and the equivalent UVI figure on a low-cost 16×2 LCD module with an I^{2}C serial interface.

Fig.6 shows how an Arduino Uno can be connected to both the UVM30A module and the LCD with the I^{2}C interface attached.

The resulting sketch file is called **Arduino_UVI_meter_sketch.ino** and is available from the May 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

When you upload it to the Arduino, it first gives you this opening display:

```
Silicon Chip
 UVI Meter
```

Then, after pausing for two seconds, it starts measuring the output voltage from the UVM30A module. It converts the reading into the equivalent UV Index and displays both, like this:

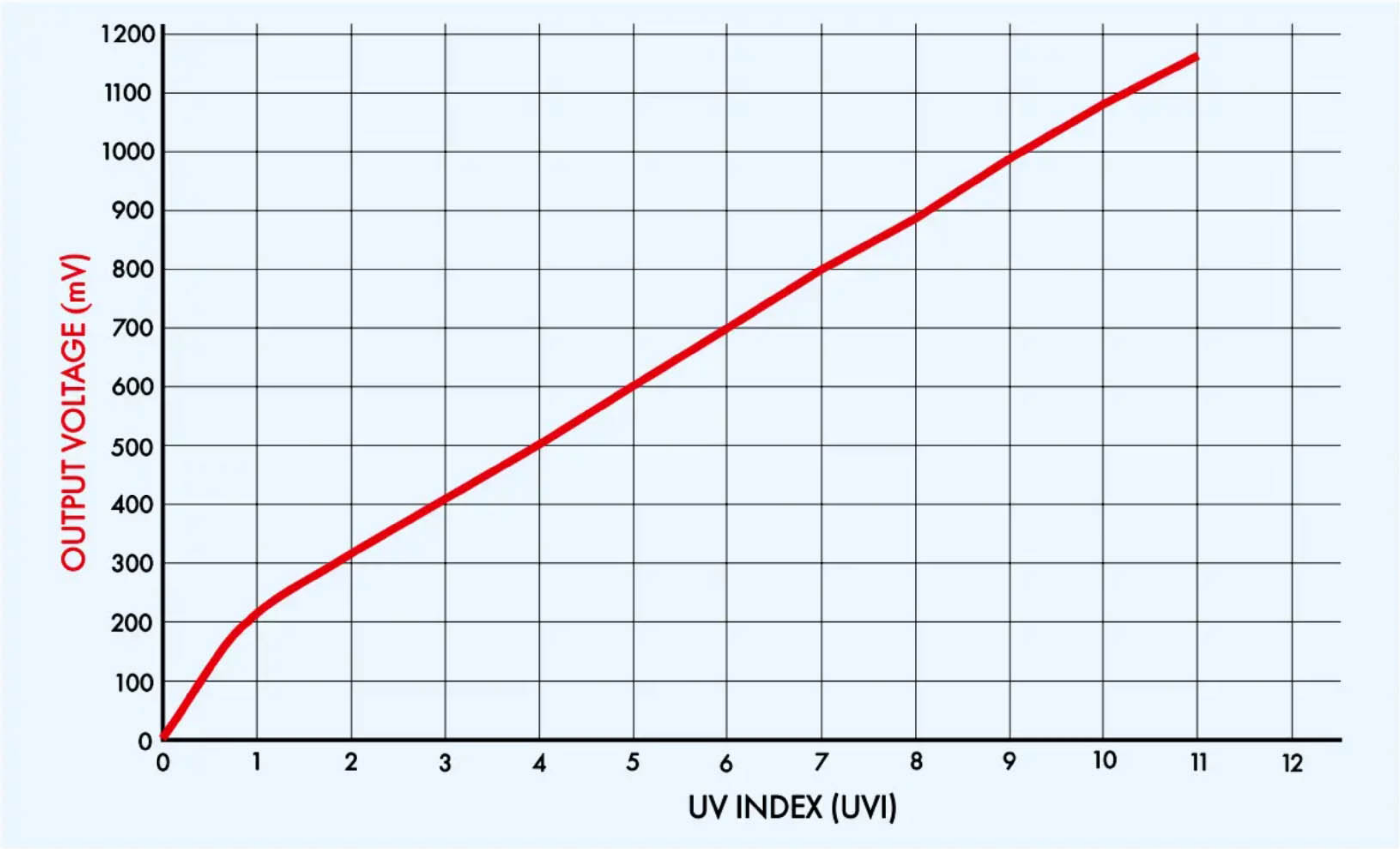
```
UV Index = 2
Vout  = 350mV
```

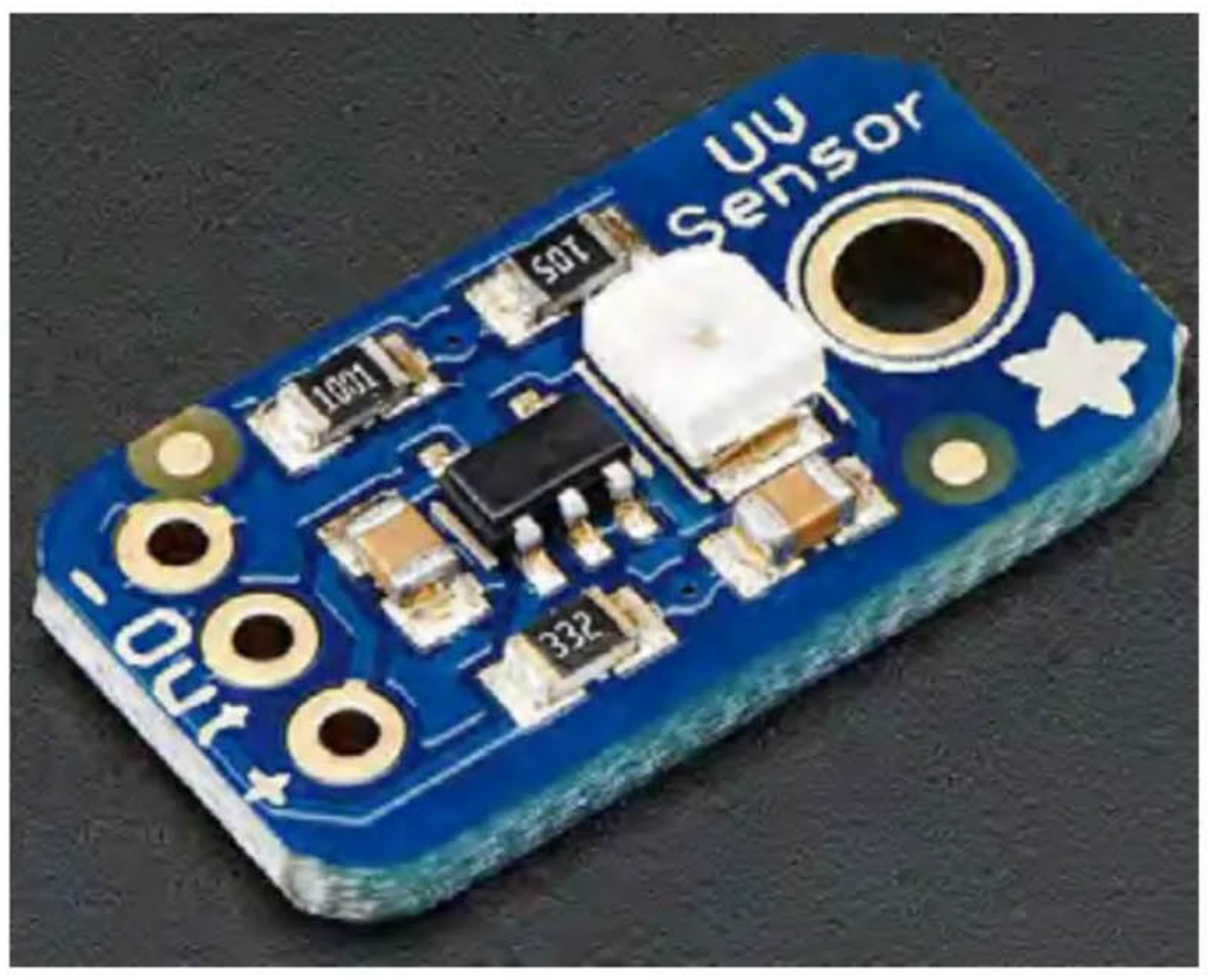
It repeats this every 1.5 seconds. The sketch also sends this data back to your computer via the Serial Monitor (if you have it connected).

So it is easy to hook the UVM30A UV sensing module up to an MCU like the Arduino and make yourself a handy UVI meter. The sketch could also be adapted to MMBasic code for use on a Micromite or Maximite; any microcontroller with an analogue input should do.

One morning in late October, I took this arrangement outdoors and got UVI readings of 1-2 when the Sun was only about 30° above the horizon.

The readings steadily rose as the morning wore on (although they





Shown above, right is the Adafruit version of the UV sensor. It uses the same GUVA-S12SD sensor IC as the Altronics version.

Fig.5: the mapping of the output of the UV sensor to the UV index is primarily linear, except below a UV index of one. Therefore, the formula to convert its output voltage to the UV index is pretty simple. The sketch source code (available for download) shows exactly how it's down.

UV Radiation and UV Index

Ultraviolet or UV radiation is electromagnetic radiation with wavelengths between 10nm (nanometres) and 400nm – shorter wavelengths than light that is visible to humans, but longer than the wavelength of X-rays.

UV radiation constitutes about 10% of the total radiation from our Sun. Still, this radiation is the primary cause of suntan, sunburn and skin damage resulting in skin cancers.

The section of the solar UV radiation spectrum primarily of interest regarding human skin safety is between 100nm and 400nm. This is subdivided into three main divisions: UV-A (315nm to 400nm; 'long wave UV'), UV-B (280nm to 315nm; 'medium wave UV') and UV-C (100nm to 280nm; 'short wave UV').

Although photons of UV-C radiation carry more energy than those of UV-B or UV-A and are therefore more capable of skin damage, the good news is that virtually none of the Sun's UV-C radiation ever reaches the surface of the Earth. These photons are absorbed by oxygen and ozone in our upper atmosphere.

Most of the UV-B radiation from the Sun suffers the same fate, especially when there is heavy cloud cover.

When there is cloud cover, more than 95% of the solar UV radiation reaching the surface of the Earth consists of the longer UV-A wavelength. And these wavelengths are of concern when it comes to protecting our skin. So clouds tend to reduce the amount of UV reaching the surface but do not eliminate it; you can still get sunburn on a cloudy day.

The UV Index is an international measurement scale used to indicate the intensity of UV radiation in easily understood terms for the 'general public'. It uses a scale of 11 or more steps, with each step corresponding to an increase of UV radiation intensity of 25mW/m^2 (milliwatts per square metre). A UVI of one indicates a UV intensity of 25mW/m^2, two indicates an intensity of 50mW/m^2 and so on.

Fig.7 shows the UV Index on the right and the corresponding UV radiation intensity on the left. The coloured bands indicate the five categories into which the UVI levels are grouped in terms of their 'risk of harm' to our skin.

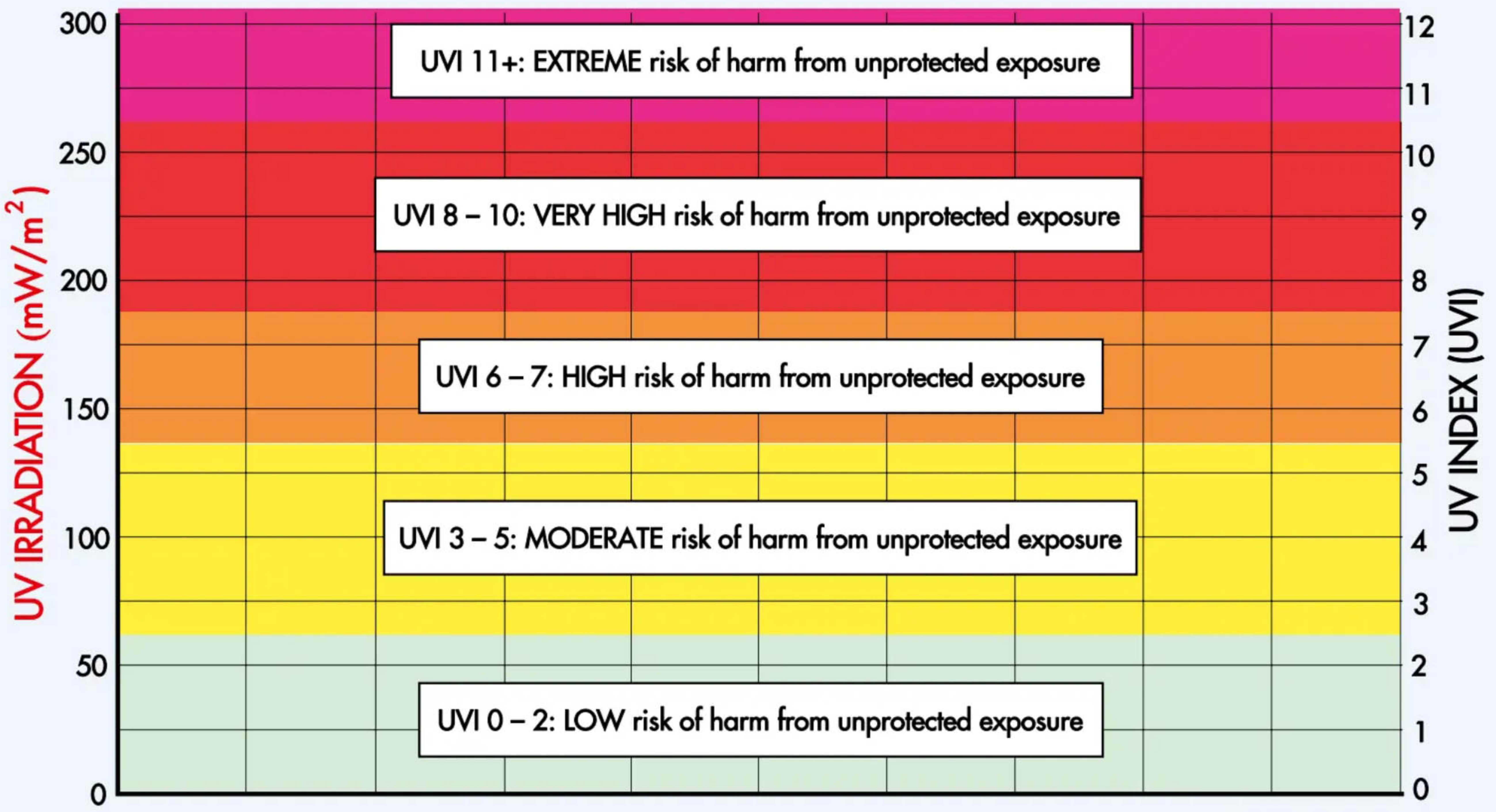


Fig.7: this shows the five ranges of UV index values that provide some guidance as to the danger of skin exposure under those conditions. It will depend somewhat on your skin pigmentation, but it's still a good idea to 'cover up' at the upper end of the risk spectrum.

dropped back when clouds obscured the Sun). When the Sun was directly overhead and the clouds were not obscuring it, the UVI readings reached a level of 8 or 9.

So it appears to be doing its job and should be helpful for those who spend a lot of time outdoors. By the way, the Australian Bureau of Meteorology also publishes UV Index predictions in their forecasts. For the UK, the Met Office includes UVI in its forecasts: **www.metoffice.gov.uk**

Of course, they can only give a rough idea of what to expect, whereas this module provides an actual reading of the immediate conditions that you are experiencing.

Cost and availability

I obtained the module shown in the photos from Altronics (catalog code Z6397) for around $40. If you want to source this in the UK then Amazon and eBay offer it for around £18, but at the time of writing **fluxworkshop.com** offer it for just over £14.

This version has the same circuit, but everything is mounted on a single PCB measuring only 19 × 10 × 2mm and seems to originate from the US firm Adafruit: **www.adafruit.com**

Adafruit has a smaller version (ID 1918) available for US$6.50 plus shipping. It's also available from Digi-Key in the US for around the same price.

There is yet another smaller version available from various suppliers on AliExpress. This one measures 19.8 × 10 × 2mm and is available for a few pounds with free shipping. So you have quite a good range to choose from, all with the same UV sensor and its surrounding circuit, in various sizes and prices.

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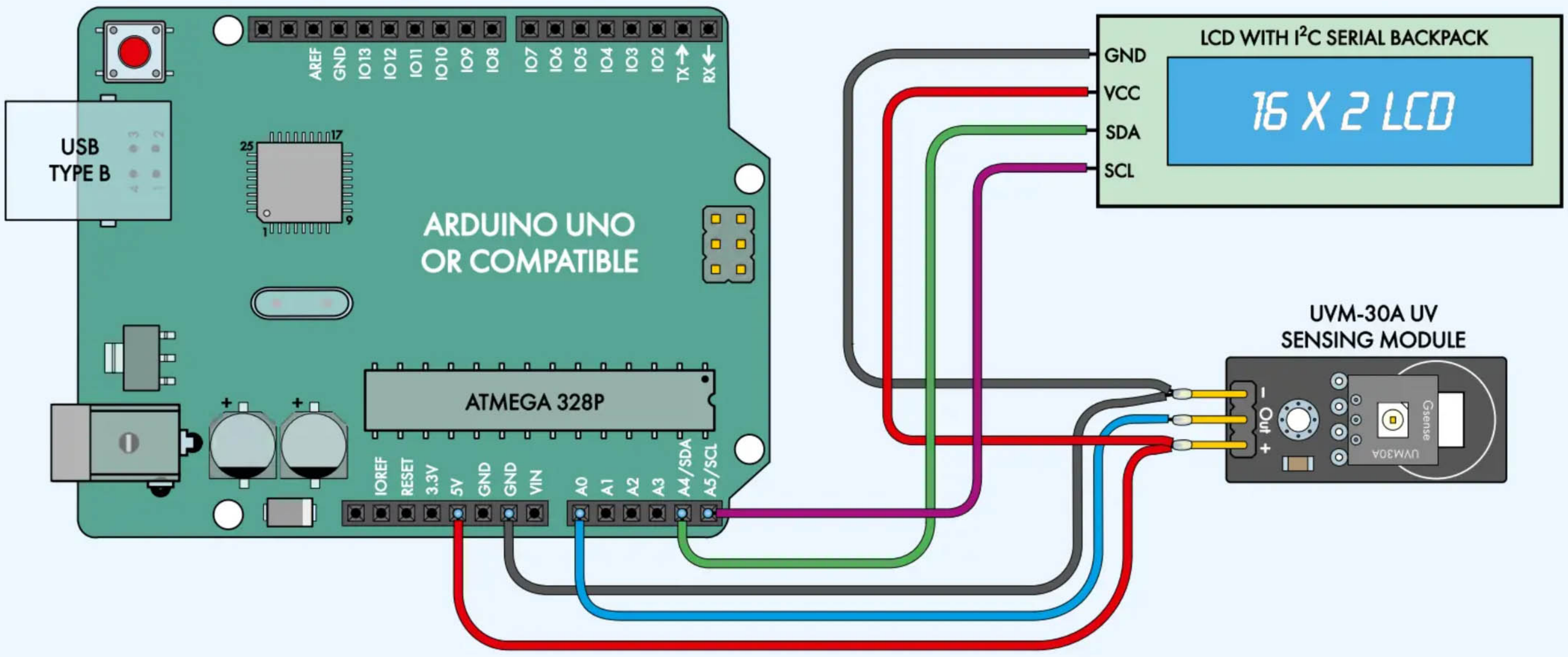

Fig.6: to make a practical device, I added a serial (I^2C) 16×2 LCD module to the basic circuit, wired as shown here. That allows the Arduino to display both the raw UV sensor output voltage and the equivalent UV index in a handy portable package if the Arduino is battery-powered.

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Songbird

Chirpy
470u

By Andrew Woodfield

Here's a decades-old design brought up to date in a new package and made to appeal to beginners as well as experienced builders. It's quick and easy to build and a great project if you're new to electronics.

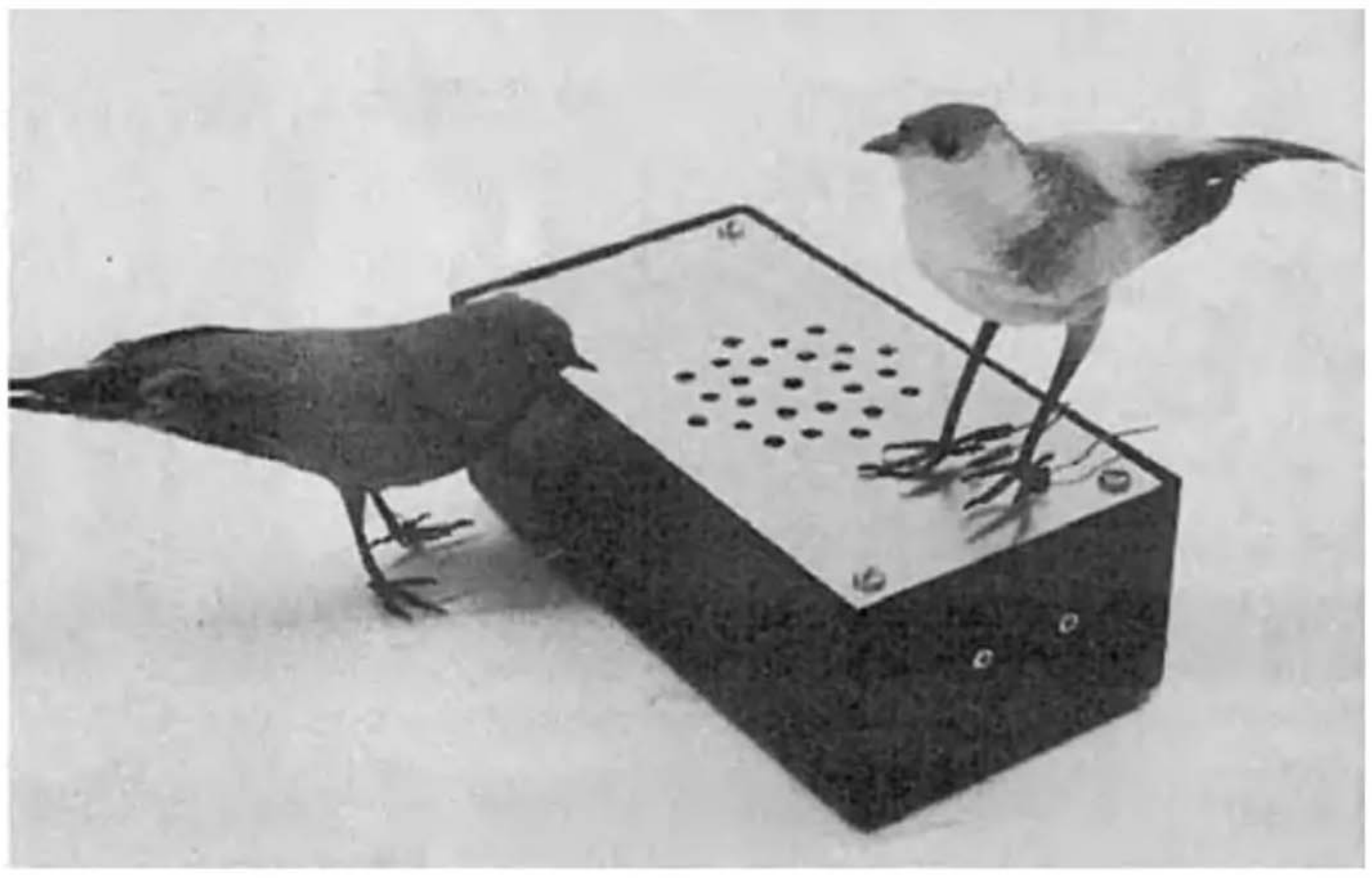
When the festive season or birthdays approach, those interested in electronics often look for a small, easy-to-build project to give as a gift. Something with flashing lights or a variety of sounds has universal appeal, especially for our (grand)children. Helping a beginner to build one of these is the perfect way to spark an interest in the hobby.

The problem is identifying a suitable design. During a recent search, I came across an 'electronic canary' designed by Ron de Jong, published in *Electronics Australia* way back in May 1981.

Unfortunately, the 74C-series CMOS chip used in the original design is not as widely available as 74HC-series devices. Also, the original design used a large square PCB mounted in a very large plain rectangular plastic box with a mostly bare aluminium front panel. I felt it lacked the visual appeal to capture the imagination of today's younger audience.

This revision was my solution. Along with migrating the circuit to the 74HC-series CMOS logic family, I also redesigned the printed circuit board (PCB) into a more compact and attractive bird shape – something between an overfed festive budgie and a kookaburra!

Modern PCB manufacturing provides a choice of PCB solder mask colours. I chose purple, but you could also go with something like green, yellow or red (after all, it was initially a 'canary'). Contrasting with the colour-coded bands of the resistors on the PCB, the overall effect is bright and cheerful. The double-sided PCB design also makes it much easier to build than the original design.



The 'inspiration' for the Songbird project came from the May 1981 edition of *Electronics Australia*. The image shown is the lead photo used for that article.

I removed the original large and costly 8Ω speaker and its driver transistor in favour of a modern, inexpensive piezo speaker. Mounted on the rear of the PCB, it produces a bright sound without driving parents to utter despair.

The original used a somewhat expensive 9V battery, while a pair of inexpensive AAA cells power my new version. The new 3V supply also significantly reduces the current draw to under 2mA.

What makes it sing?

The Songbird consists of two almost identical sets of three coupled oscillators, ie, circuits that produce a continually changing voltage level. Each oscillator uses one of the six CMOS schmitt-trigger inverters inside the 74HC14 integrated circuit (IC). Fig.1 shows the basic oscillator circuit used in each case.

The inverter (triangle) produces a low output voltage when its input voltage is high and vice versa. Connected to it are a resistor, 'R', and a capacitor, 'C'. The values of C and R vary in each oscillator.

When power is switched on, capacitor C is discharged, and the inverter input is at 'ground' potential (0V, or logic 'low' level). As a result, the

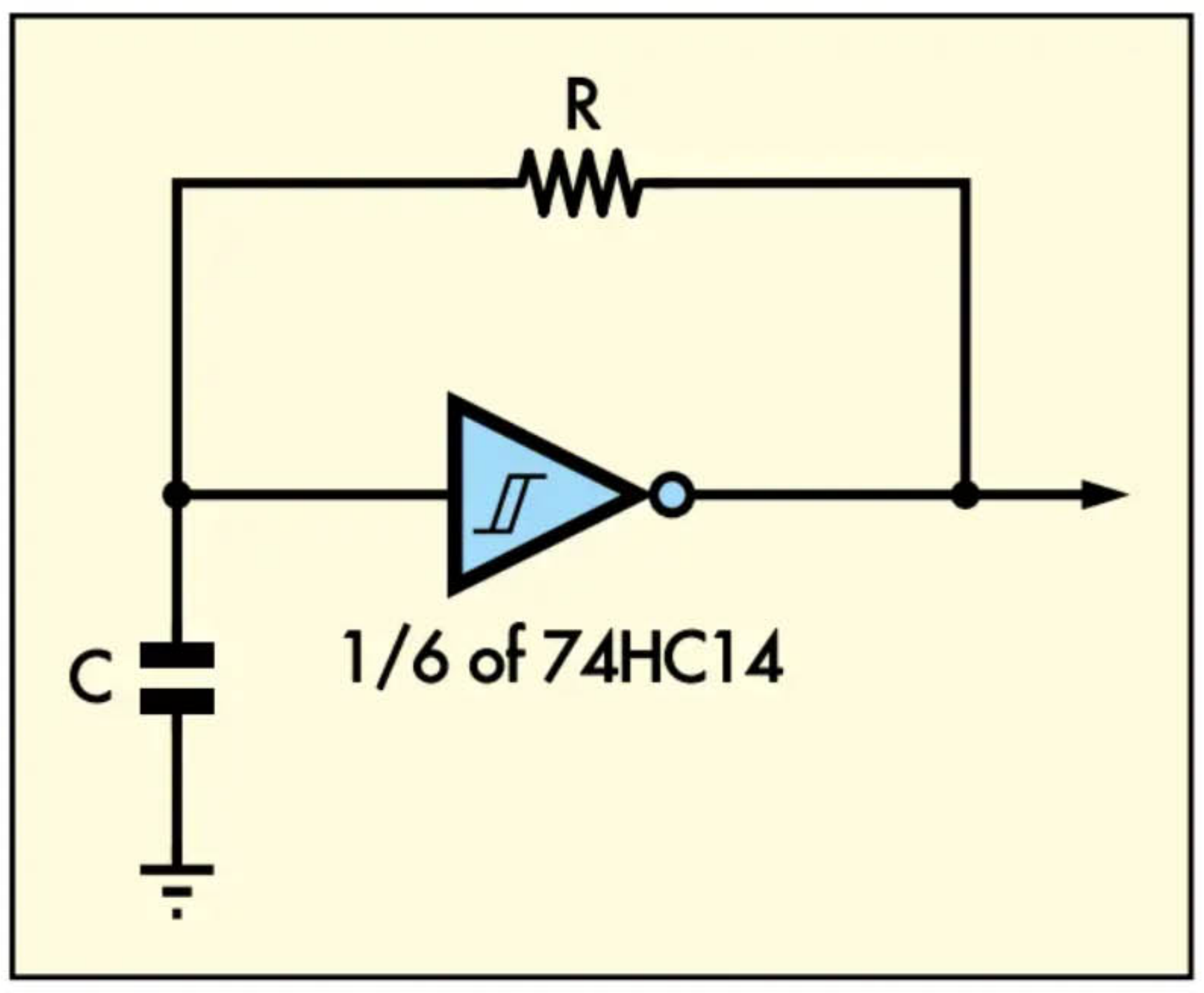


Fig.1 (above): the Songbird circuit uses six oscillators, all based on this simple RC (resistor-capacitor) oscillator configuration.

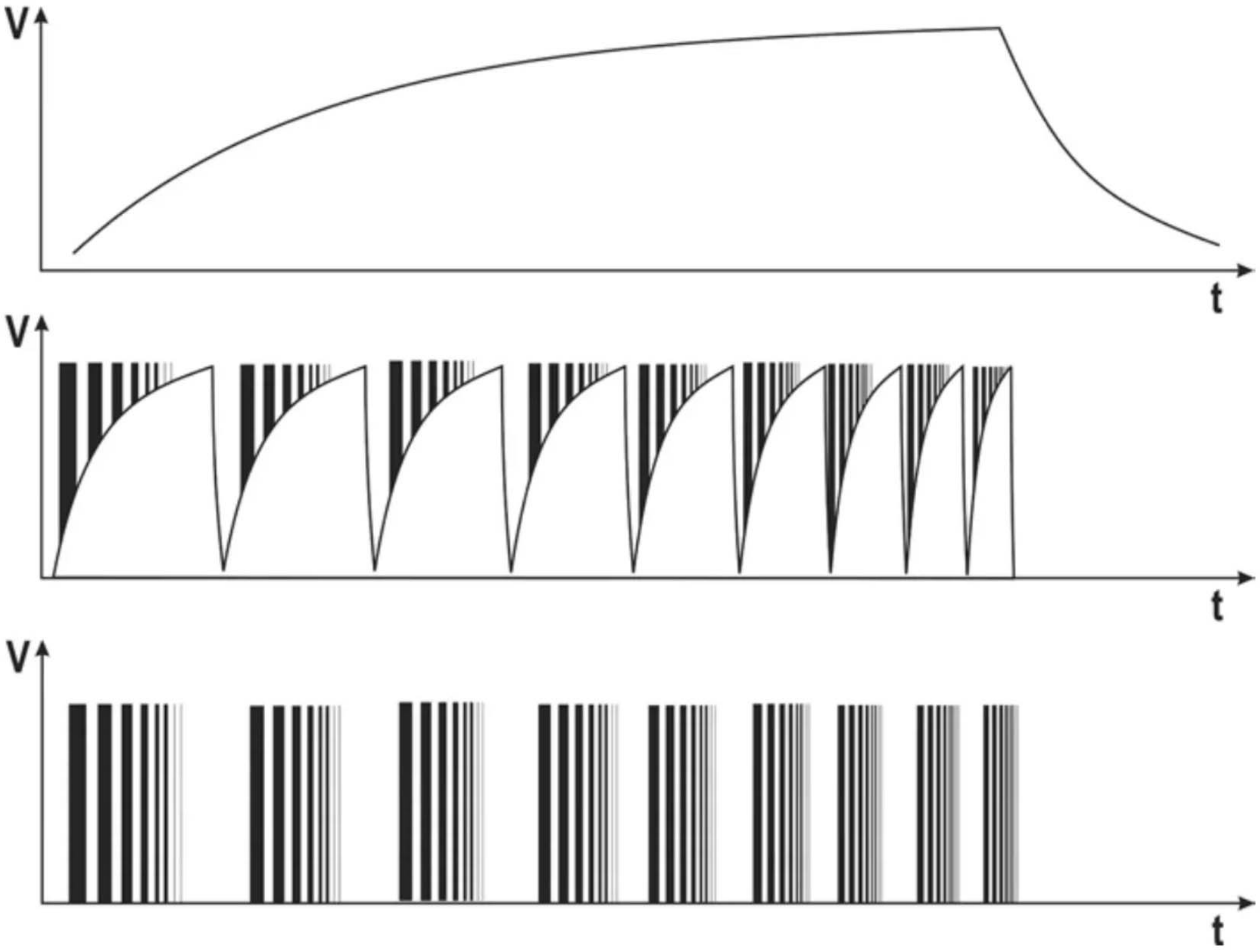


Fig.2 (right): these three waveforms are created by each set of three schmitt-trigger inverter-based oscillators.

output of the inverter is near +3V (a logic 'high' level). The voltage across capacitor C begins to rise as current from the high level at the inverter output flows via resistor R.

When the voltage across C rises above the schmitt-trigger low-to-high transition voltage (about 1.5V in this case), the inverter input recognises that the input has gone from a logic 'low' to a logic 'high'. It immediately changes the inverter's output to a logic 'low' voltage, almost at 'ground' potential or 0V.

The voltage across capacitor C starts to fall as current flows from the capacitor back to the low-level output via resistor R. When the input voltage falls below the schmitt-trigger high-to-low transition voltage (about 0.7V), the inverter input voltage is detected as a low, and output suddenly switches to high. The whole cycle then repeats.

Over many such cycles, the result is a sawtooth voltage at the input pin varying from 0.7 to 1.5V, and a square wave at the output ranging from almost 0 to 3V. The frequencies of these waveforms are identical and proportional to the product of the values of resistor R and capacitor C (the 'time constant').

The basic bird sound is made from two pairs of three of these oscillators coupled together. In each tri-oscillator group, one sets the basic timing, the second creates the chirp, while the third makes the tone of the bird sound. Other components around each oscillator modify and combine these three to produce the final sound. The resulting waveforms are shown in Fig.2.

At the top of Fig.2 is shown the timing oscillator, in the middle is the chirp oscillator and at the bottom is the note oscillator.

The full Songbird circuit is shown in Fig.3. In each oscillator, a series diode/resistor combination placed in parallel with resistor R results in an asymmetric square-wave shape by changing the resistance depending on whether the capacitor is being charged or discharged. Different capacitor and resistor values in each set of three timing-chirp-note oscillators produce two slightly different bird sounds.

These signals are combined by using each output to drive one side of the relatively high-impedance piezo speaker, which produces the final desired bird sounds.

The circuit is powered by a battery, shown at upper-right in Fig.3, comprising two 1.5V cells in series to produce 3V. It is connected to the circuit via switch S1, which acts as a power on/off switch. A 100µF capacitor stabilises the battery voltage so that it does not vary in the short term as the oscillators draw varying currents.

Building the Songbird

Remember that this is designed to be an ideal beginners' project, so the following description is primarily written for those with limited experience. Children from around nine or ten years of age can build it (with help). However, it's equally suitable for those interested in building a little project that is just a bit different. Simply put, you can never be too old to build the Songbird!

The basic version of the Songbird uses a simple unetched PCB as the base.

If using the battery box with an integral switch, the base will need to be slightly wider (63mm) as the box is longer than the holder shown here. Still, it does save you from having to mount and wire up the switch.

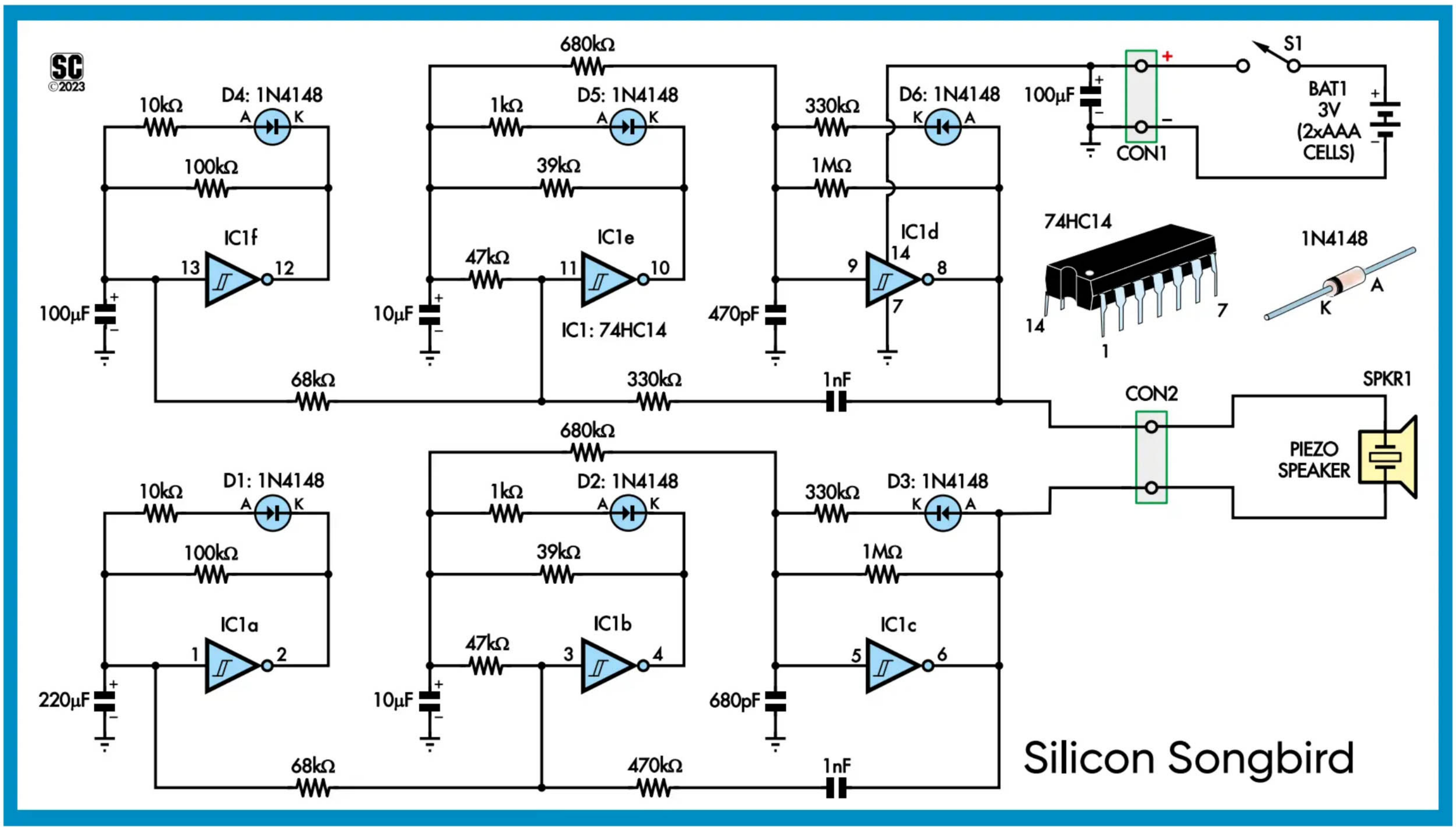


Fig.3: the full circuit of the Songbird replicates the oscillator configuration shown in Fig.1 six times. This is convenient as IC1 contains six inverters, so only one chip is needed. Each triplet of oscillators uses a different set of feedback components to produce different frequencies. They are ganged up via resistors and capacitors, ultimately feeding the piezo speaker together via connector CON2.

Children and beginners will need help from a more experienced builder, given the inherent risks of a hot soldering iron and other possibly dangerous tools like side-cutters.

The instructions assume it will be built in four stages, each taking between 20 and 45 minutes. You might prefer to make it in several shorter 10-to-15-minute bursts to better match a younger child's concentration. For the more experienced, you can probably build the whole thing in about 1½ to 2 hours.

Still, there's no rush. The Songbird will happily wait to burst into song until you're finished. You will likely make fewer mistakes if you take your time. Check each part before soldering and enjoy the relaxed pace of the construction process.

Some tools you'll need include:

1. A 15-25W soldering iron with a fine to medium tip. Keep this clean by carefully wiping the tip periodically on a damp rag or sponge.
2. 0.5-1.0mm fine rosin-cored solder. If this is your only project, a 15g 'hobby tube' will be enough
3. Sharp pair of small side cutters.

Other useful tools include:

4. Fine needle-nosed pliers or a component bending jig (Jaycar Cat TH1810 or Altronics Cat T1495); these bend the component leads.
5. A soldering iron holder – it helps you to avoid accidental contact with the iron's hot tip! A good soldering station will come with one.
6. A 'solder sucker' desoldering tool and/or solder wicking braid – these help you to remove solder if you get it in the wrong place or incorrectly place a part and need to remove it (that can happen to anyone).
7. A multimeter – you might find this helpful for checking resistor values, checking battery voltages and testing for shorts and open circuits. They start under £5 (eg, Jaycar Cat QM1500, Altronics Cat Q1053B)!

Find a clear space to build the Songbird, such as a kitchen table, with plenty of light. Also, ensure you have good ventilation because soldering will create some fumes. Place a cloth or a layer of newspaper (or similar flat disposable material) over your working area to avoid marking the tabletop with your tools, the PCB or molten solder during assembly.

A helpful way to handle the parts during construction is to place them in a small plastic tray, say 300mm × 200mm, on one side of your workspace.

Construction step #1 (resistors)

The location for each resistor is shown in Fig.4. It's usually easiest to install the resistors in groups. Double-check the value of each resistor using its coloured bands before fitting (or even better, verify the value with a DMM set to measure ohms) because different resistors have very similar bands (eg, 1kΩ, 10kΩ and 100kΩ).

Your parts supplier may only have (smaller) 1/8W resistors or (more precise) 1% tolerance resistors, which will work just as well. 1% resistors have five bands rather than four. See the table in the parts list, which shows how they vary.

You will need to bend the leads of the resistors into a U-shape so you can insert them into the pads on the PCB, as shown in Fig.5(a). You can do this with your fingers or pliers, but it's more precise to use a lead-bending jig (available at low cost from stores like Jaycar and Altronics), as it will form the bends precisely the right distance apart. Then, insert the resistor as shown in Fig.5(b).

Solder the leads, making sure to form a shiny fillet like in Fig.5(c), then trim the excess leads using side-cutters at the height indicated by the dashed line. Protect your eyes when doing this, as the cut leads can be sharp and will fly off if you don't hold them while cutting.

Note that there are two ways to insert each resistor but the circuit will work either way. Still, it's neater to place them all in the same orientations, as in Fig.4.

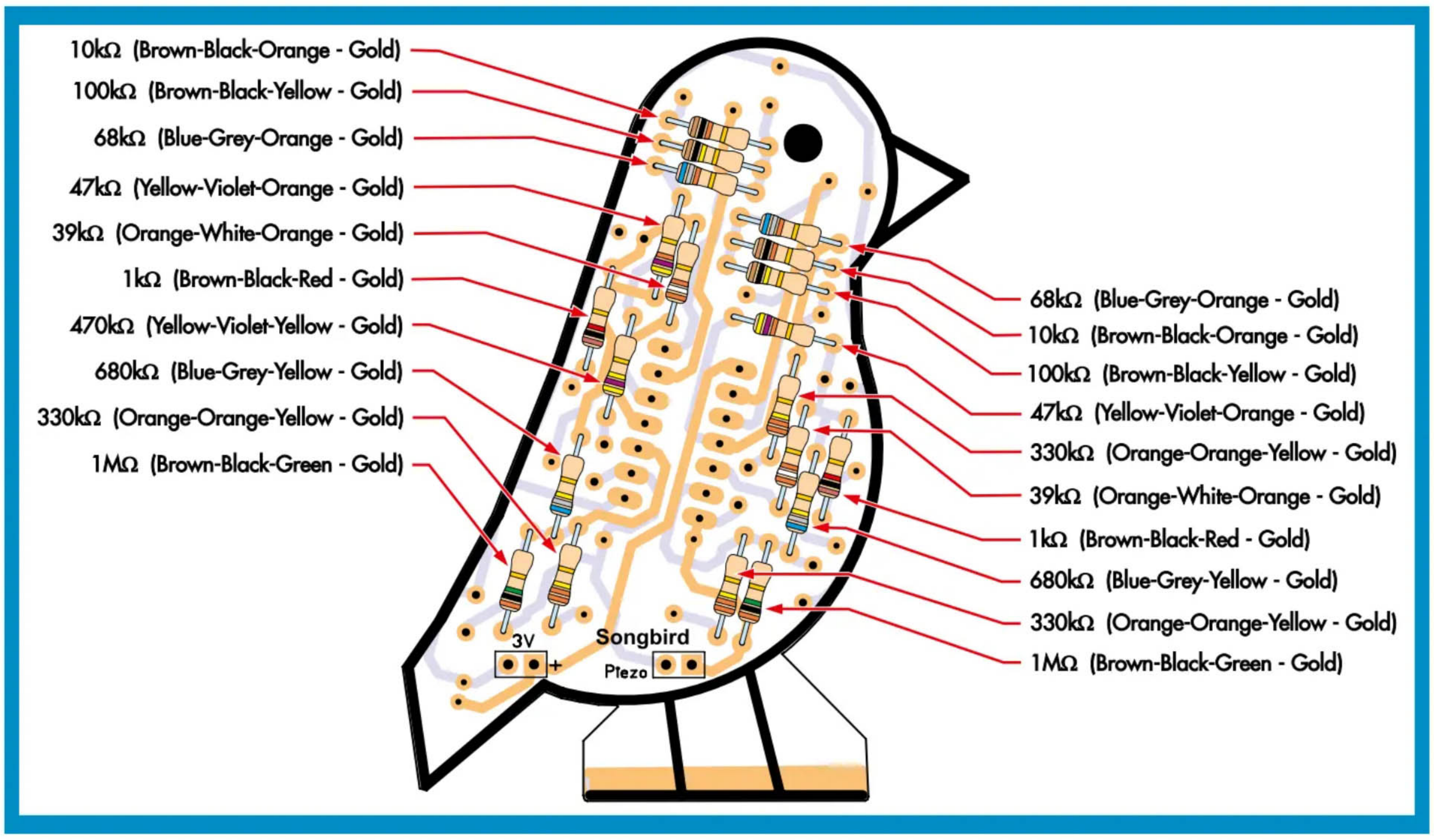

10kΩ (Brown-Black-Orange - Gold)
100kΩ (Brown-Black-Yellow - Gold)
68kΩ (Blue-Grey-Orange - Gold)
47kΩ (Yellow-Violet-Orange - Gold)
39kΩ (Orange-White-Orange - Gold)
1kΩ (Brown-Black-Red - Gold)
470kΩ (Yellow-Violet-Yellow - Gold)
680kΩ (Blue-Grey-Yellow - Gold)
330kΩ (Orange-Orange-Yellow - Gold)
1MΩ (Brown-Black-Green - Gold)
68kΩ (Blue-Grey-Orange - Gold)
10kΩ (Brown-Black-Orange - Gold)
100kΩ (Brown-Black-Yellow - Gold)
47kΩ (Yellow-Violet-Orange - Gold)
330kΩ (Orange-Orange-Yellow - Gold)
39kΩ (Orange-White-Orange - Gold)
1kΩ (Brown-Black-Red - Gold)
680kΩ (Blue-Grey-Yellow - Gold)
330kΩ (Orange-Orange-Yellow - Gold)
1MΩ (Brown-Black-Green - Gold)
3V
+
Songbird
Piezo

Fig.4: this shows the shape of the Songbird PCB and where each resistor is soldered. The colour bands are shown for four-band (5%) resistors; see the parts list for the equivalent five-band codes. It's still a good idea to check them all using a DMM set to measure ohms, as some colours can be easily confused (eg, red and orange).

Construction step #2 (diodes and capacitors)

Next, fit the six diodes as shown in Fig.6. These are all the same type, but your diodes may have a slightly different body colour to those shown here. Their size is exaggerated for clarity in Fig.6; the important thing is that, in each case, the black stripe on the end of the glass body must face down or to the right as shown.

Bend each diode's leads as you did for the resistor. When you insert it, make sure to align the diode's black band with the band printed on the PCB overlay. Solder and trim the leads in the same way as for the resistors.

Next, fit the four ceramic capacitors, shown in yellow in Fig.6. Two have the same value. Take care to place the correct part in the right location, although they are non-polarised, so it doesn't matter in which of the two possible orientations you fit them. The PCB silkscreen overlay shows the value of each capacitor to help you.

Ceramic disc capacitors may be marked in various ways. The most common markings are shown in Fig.6. After fitting each component, solder and trim the leads similarly to before.

Next, fit the three smaller axial electrolytic capacitors, which are mounted on the top side of the PCB. They come in metal cans with a plastic covering except at the top. Electrolytic capacitors are polarised, meaning you must orient them correctly. The negative lead is marked by a stripe on the capacitor body, while the overlay diagram indicates where the longer positive lead is inserted.

Once they are in the right places and have the correct orientations, solder each capacitor and trim the leads. The two larger electrolytic capacitors go on the rear side, allowing the Songbird's eye to be more clearly seen. Mount them last.

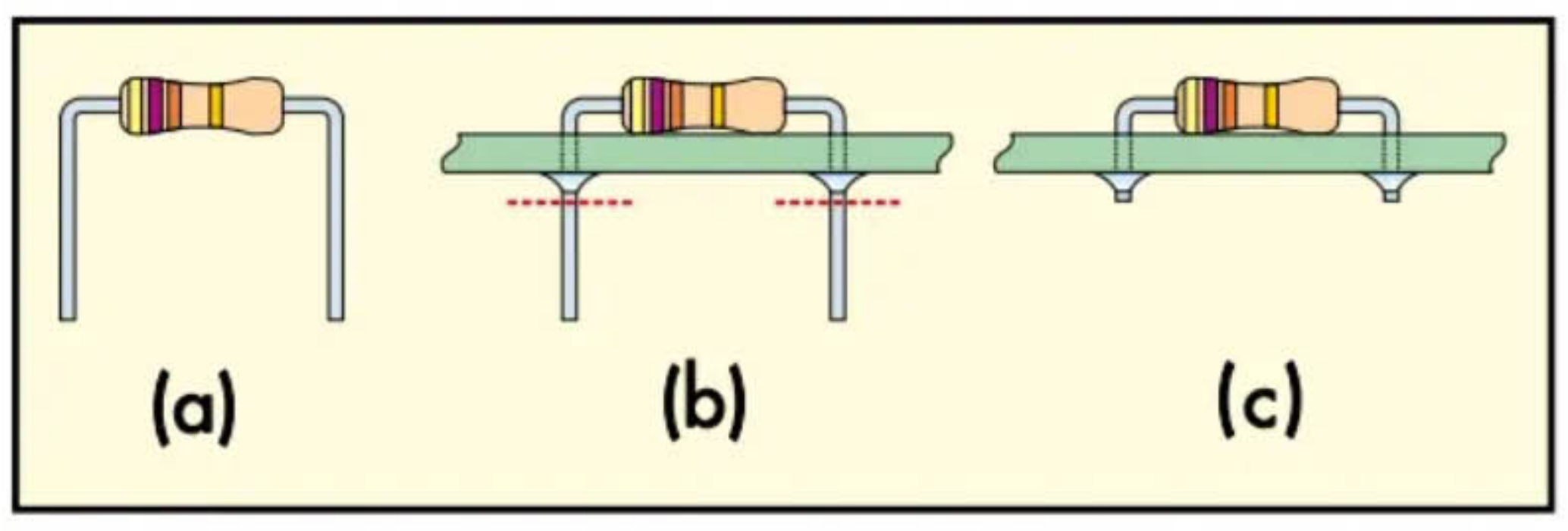


Fig.5: each resistor should be (a) bent to shape, (b) placed down on the PCB, soldered, and then trimmed with side cutters (dotted line height) to produce the result at (c).

Construction step #3 (the integrated circuit)

You must fit the 74HC14 CMOS IC to match the pattern shown on the white PCB overlay. One end of the IC is marked by a notch in its body (some ICs have a divot or dot in the nearby corner instead). This end goes closest to the Songbird's eye, as shown in Fig.8.

Before trying to fit the IC, it's helpful to slightly bend each row of IC pins until they are close to parallel. Gently roll each side of the IC towards the ends of the pins on a hard flat surface, as shown in Fig.7, so that the IC pins lie parallel (or close to it). You can also buy a tool to do this (again, check Jaycar and Altronics), which is easier to use, but the flat surface method does work well provided you are careful.

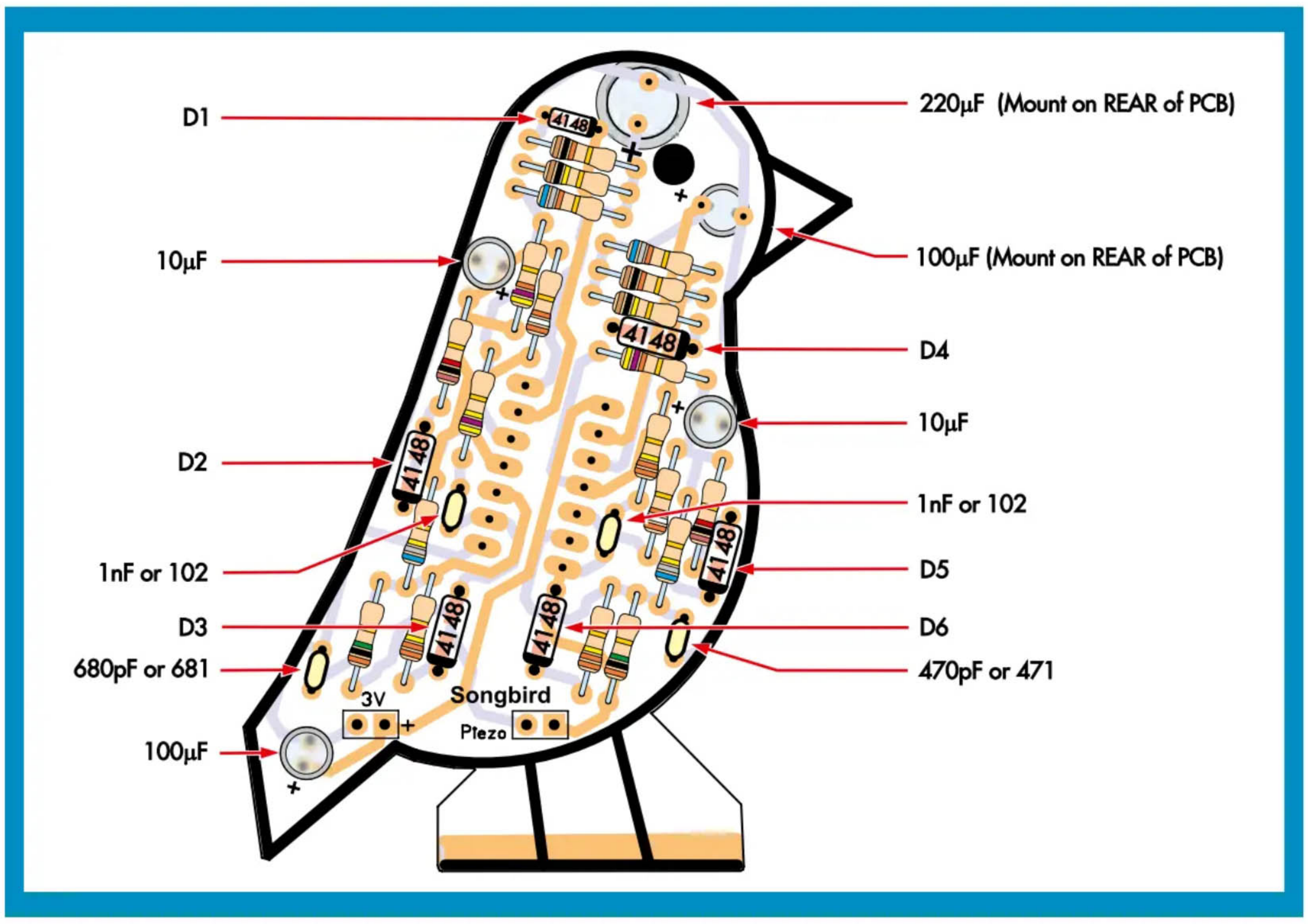
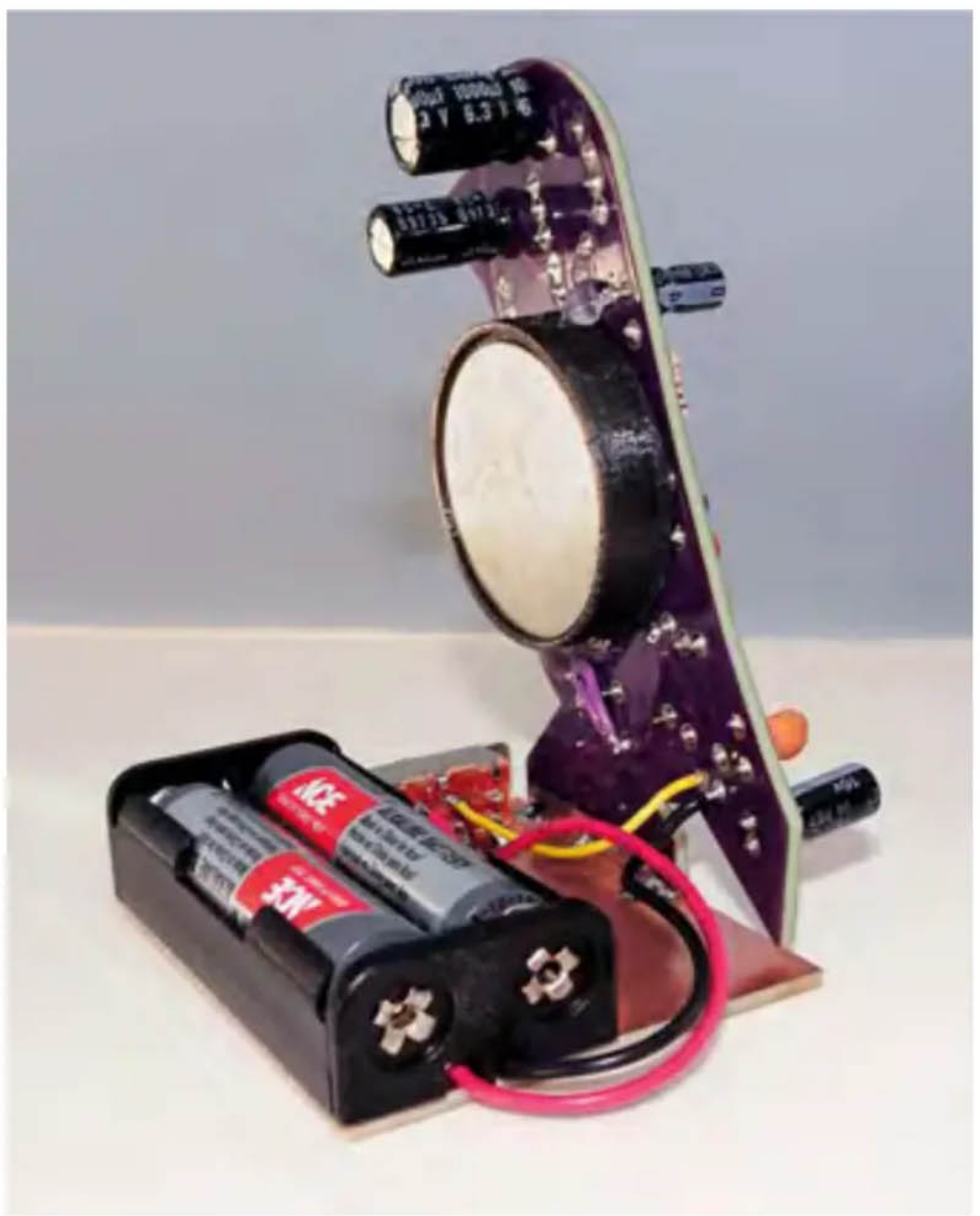

D1
10µF
D2
1nF or 102
D3
680pF or 681
100µF
220µF (Mount on REAR of PCB)
100µF (Mount on REAR of PCB)
D4
10µF
1nF or 102
D5
D6
470pF or 471
4148
3V
+
Songbird
Piezo

Fig.6: this diagram will help you to fit the diodes and the capacitors on the Songbird's PCB. The ceramic capacitors are not polarised and can go in either way around. However, the electrolytic capacitors must have their longer leads inserted in the pads marked with a + (the stripe on the can indicates the opposite, negative lead). Similarly, the diodes must be fitted with the cathode stripes facing as shown.



The 'basic' version of the Songbird. The main PCB is soldered along its base to a single-sided unetched PCB. The battery holder and slide switch are also mounted to the unetched PCB.

Parts List – Songbird

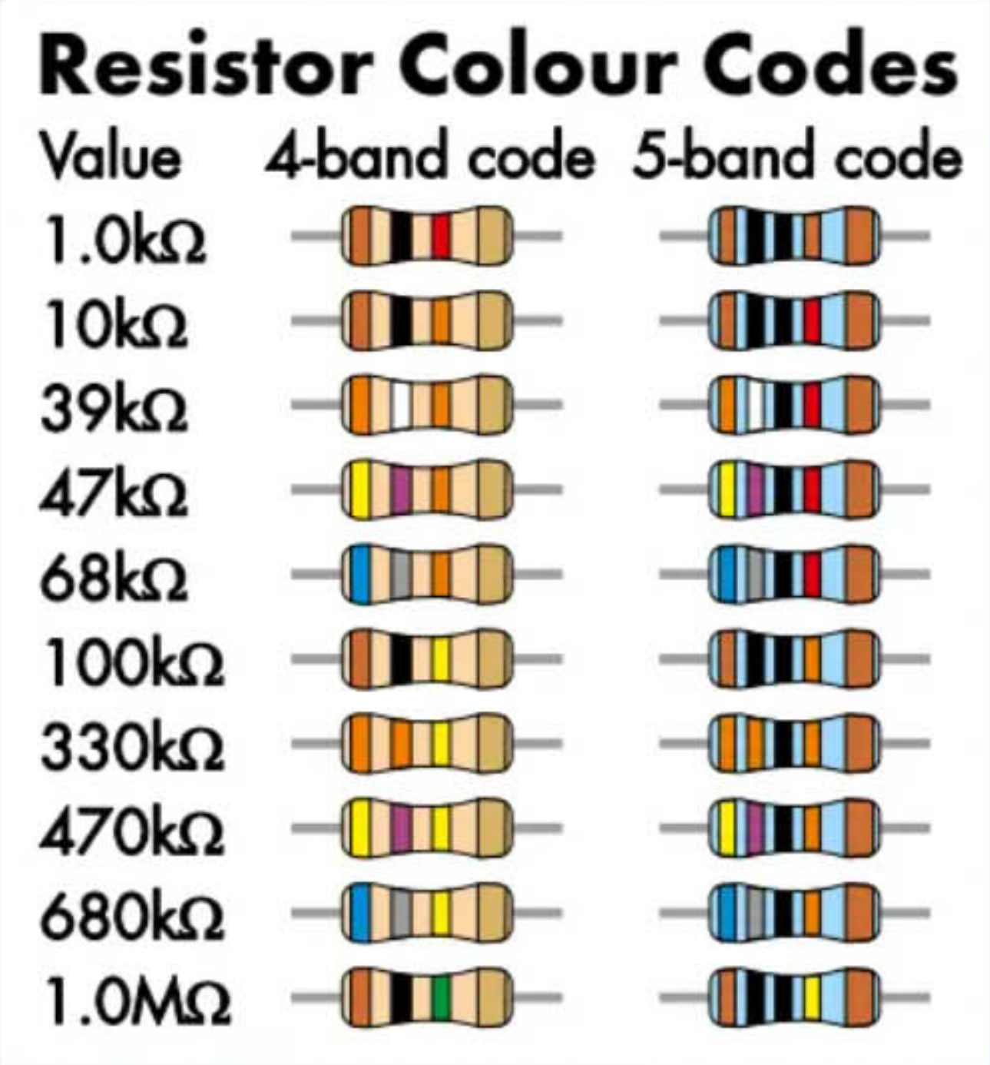
1 double-sided purple, green, yellow or red PCB coded 08103231, 61 × 75mm
1 2×AAA switched battery box with flying leads (BAT1+S1) ***OR***
1 2×AAA battery holder and toggle or slide switch (BAT1/S1)
1 27mm diameter piezo loudspeaker (SPK1)
1 52 × 45mm (63 × 45mm if using battery box) unetched copper-clad PCB (**optional**; stand for basic version)

Semiconductors
1 74HC14 hex schmitt-trigger inverter, DIP-14 (IC1)
6 1N4148 75V 200mA diodes, DO-35 (D1-D6)

Capacitors
1 220µF 16V radial electrolytic
2 100µF 16V radial electrolytic
2 10µF 16V radial electrolytic
2 1nF 50V ceramic
1 680pF 50V ceramic
1 470pF 50V ceramic

Resistors *(all ¼W axial, 5% or better)*
2 1MΩ
2 680kΩ
1 470kΩ
3 330kΩ
2 100kΩ
2 68kΩ
2 47kΩ
2 39kΩ
2 10kΩ
2 1kΩ

Resistor Colour Codes



Now fit the IC into the PCB as illustrated in Fig.8 and solder all the pins. You don't need to trim the pins after soldering, as they should only just project through the other side of the PCB.

Construction step #4 (speaker and battery)

There are two ways to complete the Songbird. You can use a simple square PCB for the base. This version is quick and easy to build. Alternatively, you can create a more elaborate birdcage and base. That will take more time, but it gives a more attractive finish to the project.

Option 1 – simple PCB base

The photo at upper left shows the basic version with the PCB mounted to a single-sided, unetched 52 × 45mm PCB base by soldering a few spots along the lower edge of the Songbird PCB. The result is surprisingly robust.

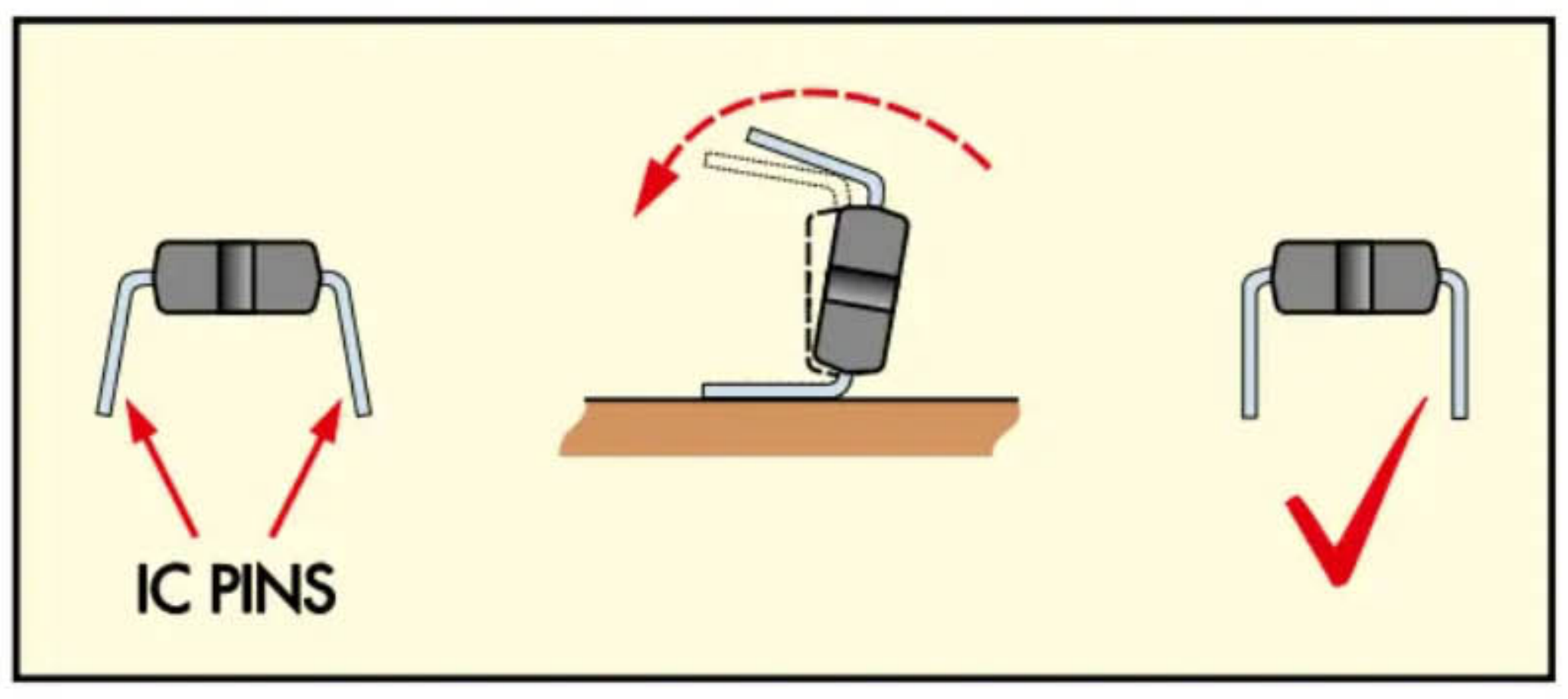


Fig.7 (above): bend the IC pins carefully to be approximately parallel before inserting them into the PCB. It's better to use a lead straightening tool, but easy enough to do it with a flat surface as long as you don't apply more force than needed.

The double AAA-cell battery holder and slide switch are then mounted directly to this blank PCB, the former with a couple of drops of epoxy glue and the latter by soldering three of the unused lower tags of the slide switch to the blank PCB base.

Note that kits will include a battery box with an integral switch, simplifying construction somewhat. The kit will also have a double-sided tape pad that you can use to stick that box to the base very easily and quickly. Since the battery box is a bit longer than a simple battery holder, it would be best to use a 63 × 45mm unetched PCB for the stand in this case (not included in the kit).

Alternatively, you could use hot melt glue or silicone sealant to attach the Songbird PCB to the side of the battery box. Just make sure you can still open it to replace the cells!

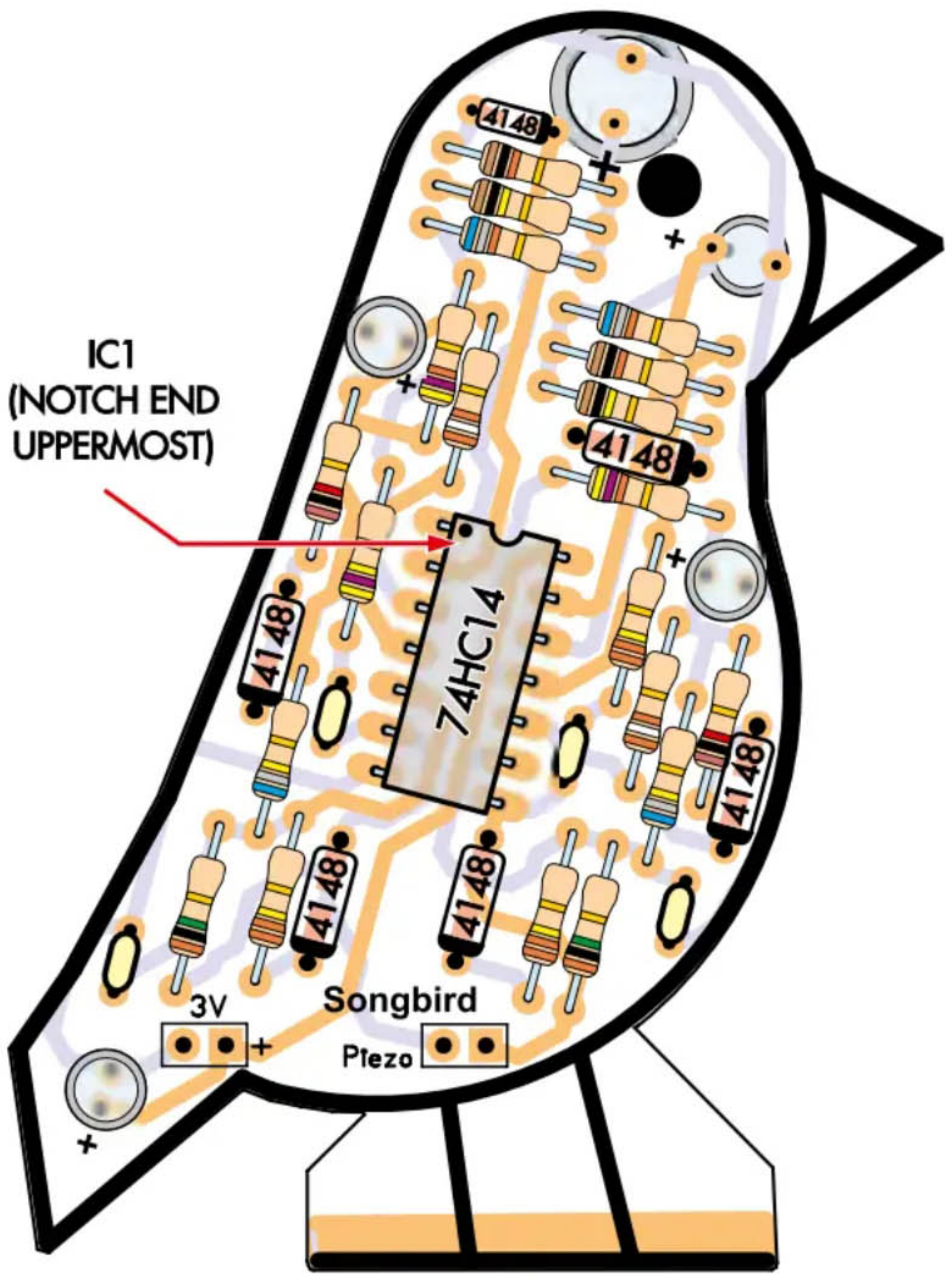


Fig.8 (right): the 74HC14 hex inverter IC must be fitted with its notch (pin 1 marking) matching the pattern printed on the PCB, as shown here.

The piezo speaker can be mounted on the rear of the main PCB using a 3D-printed speaker mount (see Fig.9) and a couple of dabs of hot glue. You could print this yourself if you have a 3D printer – STL files for all the 3D-printed items used in this project are available from the May 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

The two piezo speaker wires may be connected either way around to the PCB at the two points marked 'Piezo' on the overlay, as shown in Fig.10. You can trim the wires slightly if they are too long before soldering them in place. These wires may be almost any colour, and some can be pretty delicate, so a little care is required.

Finally, add the battery and switch wiring; the switch is not required for the battery box included in the kit, as it is already integrated into the box. In that case, you just need to connect the two wires from the box to the PCB but watch the polarity; the red wire must go to the terminal marked + on the PCB.

Option 2 – bird cage

I designed a 3D-printed base for the prototype. Those with a lathe may prefer to create a more elegant base from suitable timber. Alternately, a careful hunt around the supermarket shelves may locate a suitable 15mm-tall, 70mm diameter screw-on plastic jar lid.

The battery holder and switch can then be mounted in this base. I used a toggle switch for this, rather than a slide switch, because it's easier

The 3D-printed piezo speaker mount

The piezo speaker recommended is a low-cost 27mm diameter part commonly used in greeting cards and small toys. They are readily available from a variety of suppliers. Slightly more expensive piezo speakers are made complete with a thin pressed metal enclosure to form a resonating chamber, but they are harder to mount to the Songbird.

The 3D-printed holder used here has three benefits. It simplifies mounting (just use glue!), the sound is significantly improved, and it's all quite cheap and easy to do. It's surprising the difference this simple piezo mount makes to the overall sound volume. The piezo sits on the circular lip of the mount facing outwards. A tiny drop of super glue holds the piezo to the mount.

It's also possible to make a 5-10mm-high 27mm -diameter tube speaker mount using rolled-up paper. Produce a wall thickness of about 1mm, gluing the paper with PVA or similar glue to give it a little rigidity. Glue the circumference of the piezo speaker to the top surface of this tube with a drop of super glue, then hot glue the assembly into place on the rear of the PCB.

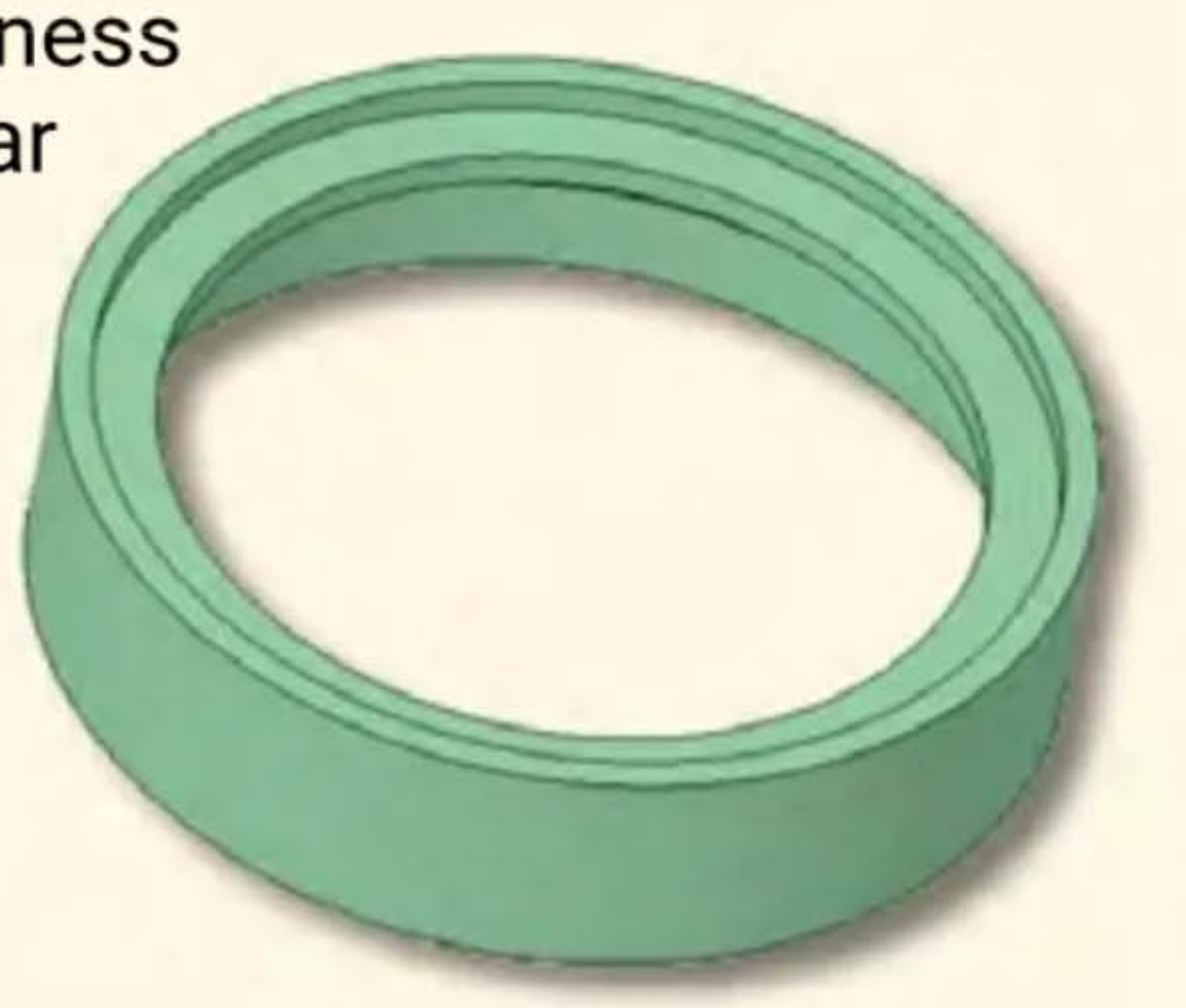
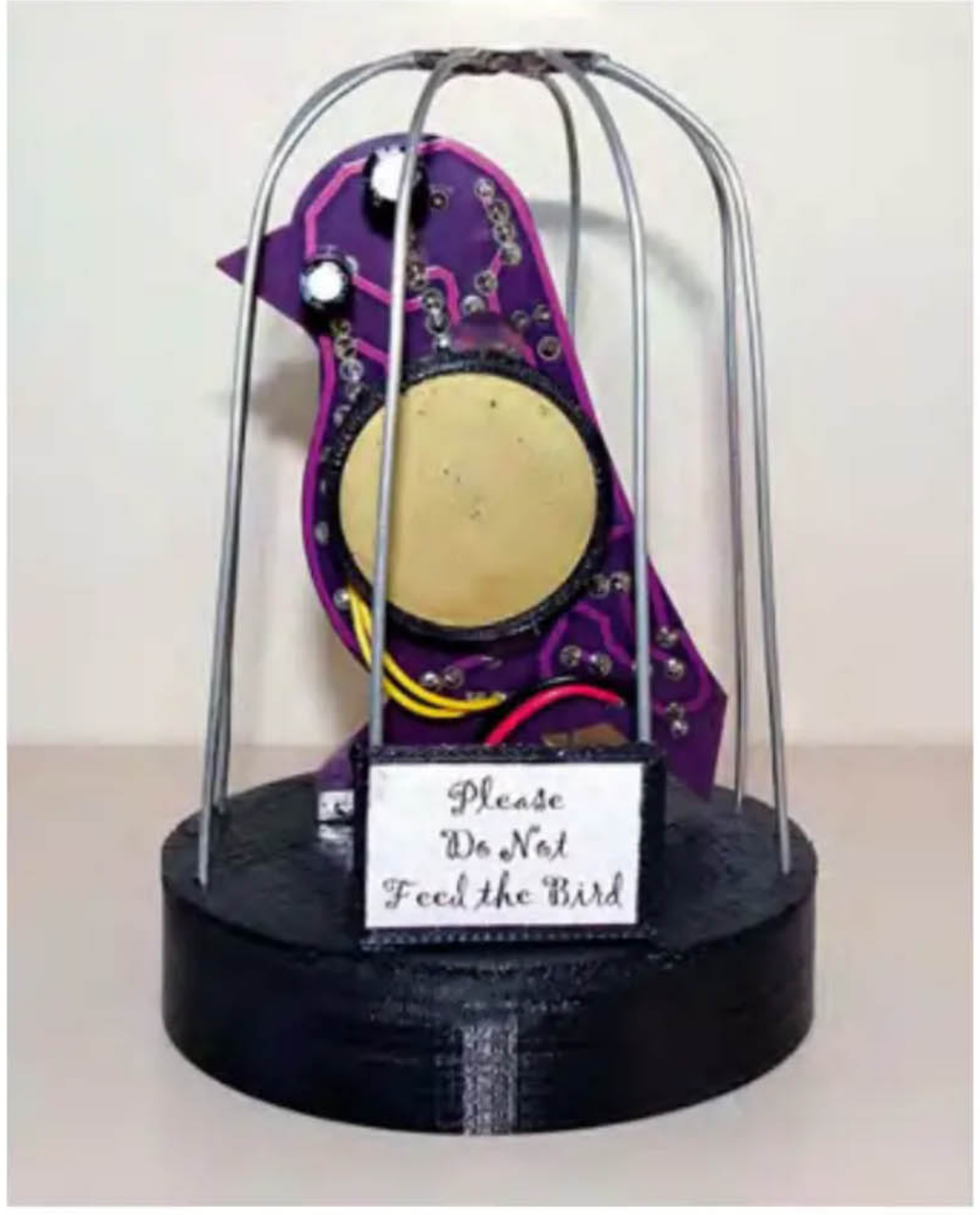


Fig.9: this simple 3D-printed speaker mount improves the sound quality and simplifies construction.



The 'bird cage' version of the Songbird uses a 3D-printed base and some wires to act as a 'cage'. The speaker is attached to the rear of the PCB using the mount from Fig.9.

to mount on a curved surface. The Songbird is then mounted on the base using two small PCB off-cuts measuring about 3 × 6mm. These are soldered on the lower edge on the rear of the main PCB, separated by a gap of about 10mm.

This method allows the Songbird to be mounted into the slot in the base and then adjusted from side-to-side in the slot to centre the Songbird in its cage. The gap in the slot is used for the wiring to the switch and battery. The wiring details inside the base are shown in Fig.11.

The piezo speaker is mounted in the same way as the basic version (Option 1). The battery and speaker wiring to the PCB is the same as shown in Fig.10.

If you prefer that the speaker is out of sight, there is enough space in the base for it to be glued there using the 3D-printed speaker holder. However, the bird sounds will be less audible.

The birdcage is made from 18-gauge (1.2mm diameter) galvanised wire and a 20mm diameter piece of tinplate. You can obtain the galvanised wire from most garden centres or hardware stores. I cut the circular piece of tinplate from a discarded tin can.

It's easiest to begin by unrolling about a metre of wire from the wire roll. Get this as straight as possible by holding one end of the wire in a vise and pulling on the other end with a pair of heavy-duty pliers. Modest force is sufficient. Then cut eight 105mm lengths from this straight piece.

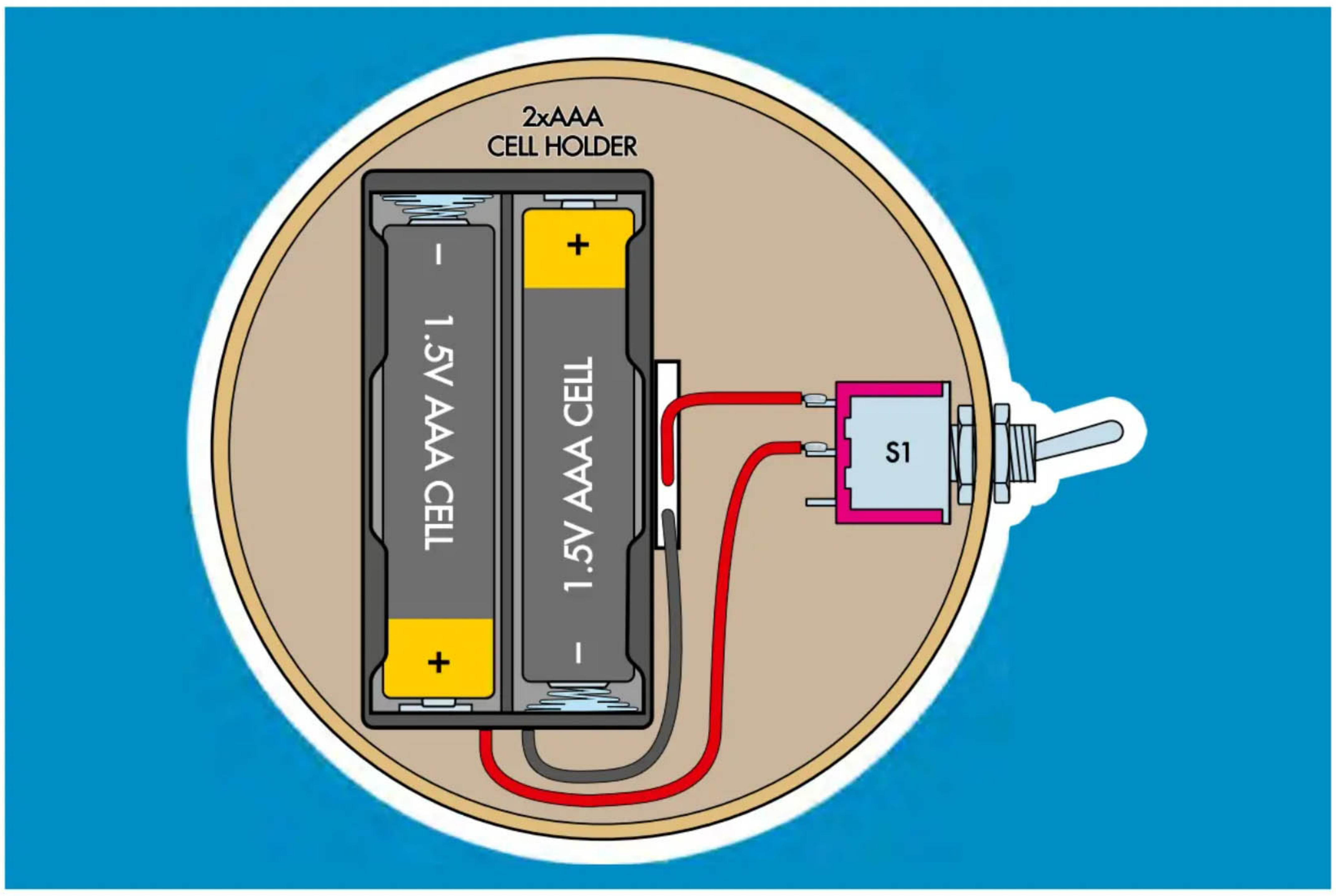


Fig.11: if building the birdcage version, glue the battery holder into the base before installing the switch and completing the wiring.

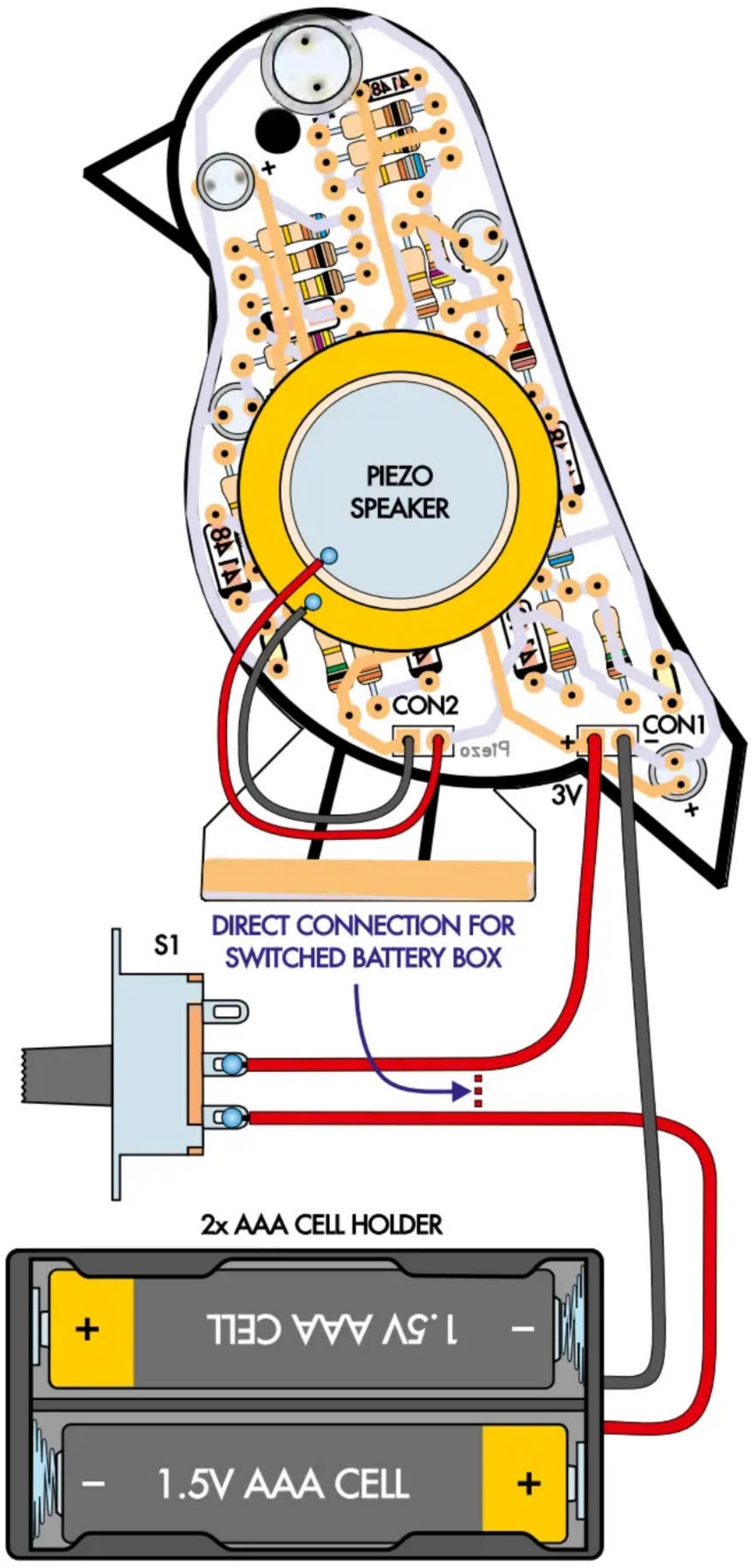


Fig.10: the battery and piezo speaker wiring are shown here. This diagram also shows the overlay markings for these connections to help you identify them. If your battery holder has an integral switch, you don't need the external switch; just run the red wire from the battery holder straight to the pad marked + on the PCB, parallel to the negative (black) wire.

Using a piece of waste timber or plywood, place these wires radially around the circular tinplate as evenly as possible. Tape them in place temporarily using short pieces of painter's masking tape. Once everything is nicely aligned – the tape really helps with this – solder the wires to the circular tinplate. The timber insulates the soldered wire and plate and protects your work surface.

Bend each wire into the final birdcage shape by hand. The wire is very easy to bend yet holds its shape well. You can then ease the ends into the eight holes in the base of the 3D-printed base or your timber base.

To ensure a good fit, you may need to drill out each of the eight holes in the 3D-printed base. This depends on the accuracy of the 3D printer. These 1.2mm diameter holes are evenly spaced on a 65mm diameter circle centred on the 70mm diameter base for those making up their own base from other materials. Add a small drop of epoxy or hot glue inside the base to hold each of the wires in place.

It all sounds complicated, but in practice, it takes surprisingly little time and effort and gives a pleasing visual finish to the project.

Adding signs

You can add the optional 'Please Do Not Feed The Bird' sign. This, and the equally optional extra sign for the other side, can be glued to the front and back of a piece of card or onto a 3D-printed frame (the latter is also available as a download). This can be glued to a suitable location on the Songbird's cage.

Operation

Turn on the Songbird's switch and the Songbird will burst into song almost instantly. The prototypes I made were joined by several additional copies as budding builders added their own efforts. The chorus of the Songbird birds produced a fantastic sound. Parents will be 'delighted' to learn that battery life is at least six months of regular use!

If you want to adjust the Songbird's sound, changing the value of the 330kΩ and 470kΩ resistors in series with the 1nF capacitors will have the most significant impact.

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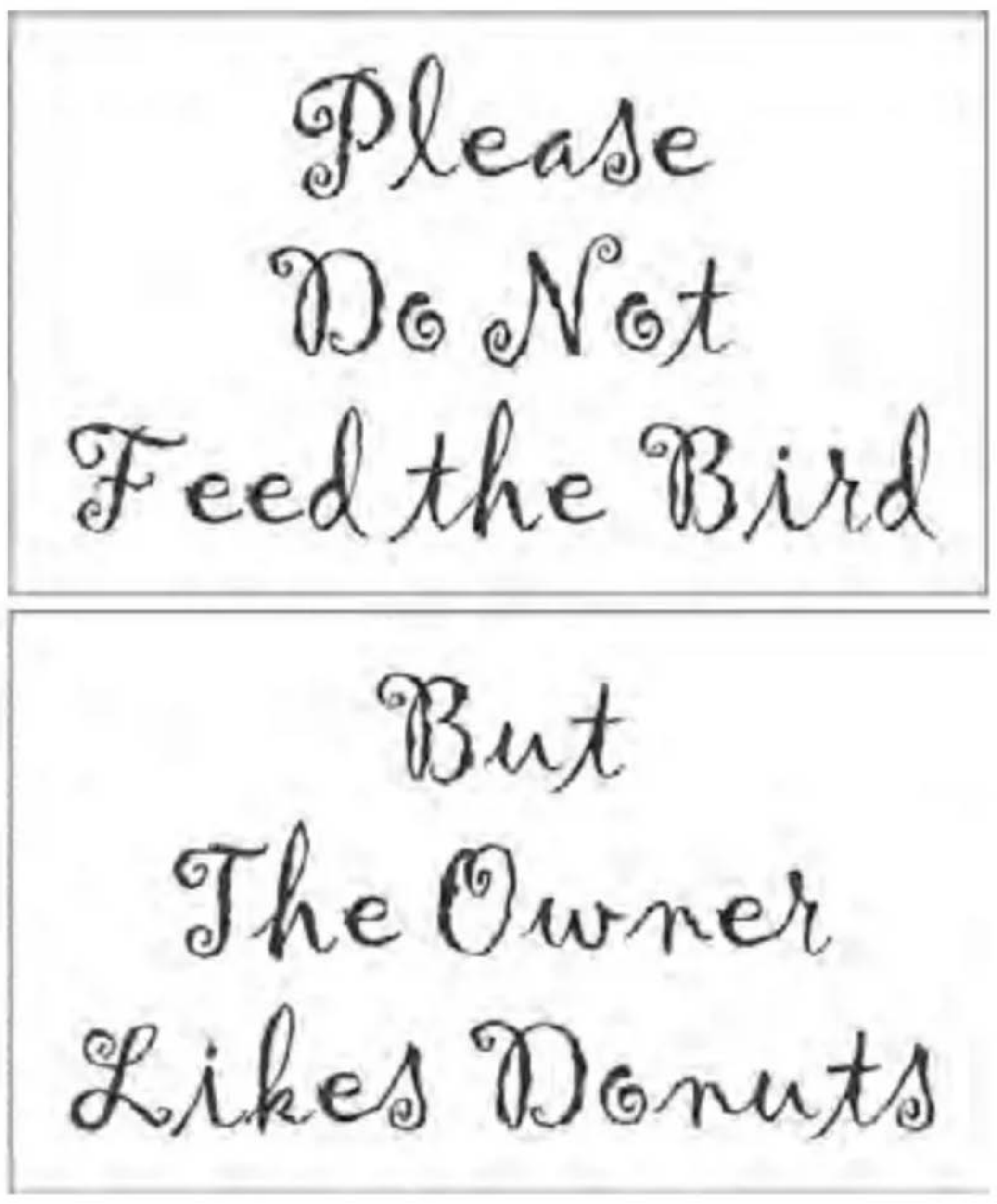

Fig.12: the optional signs for the birdcage version of the Songbird. You can download the sign artwork and 3D printer (STL) files from the PE website.

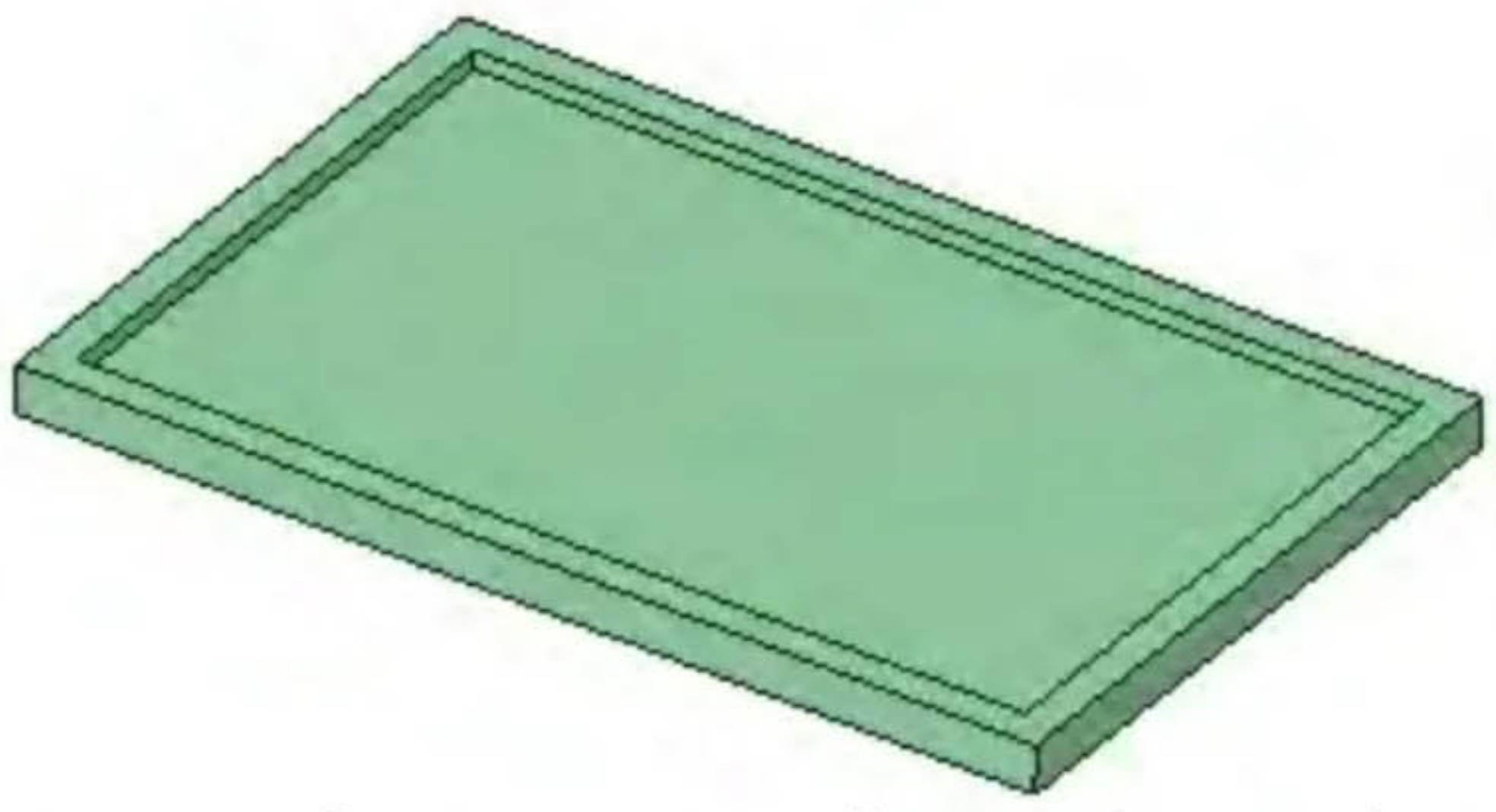

Fig.13: The 3D-printed sign frame (28 × 18mm) for holding the Fig.12 signs.

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Teach-In 2024

Learn electronics with the ESP32

by Mike Tooley

Part 3 – Analogue input and output

In the last month's part of our Teach-In series, we introduced digital I/O and showed you how to interface buttons and switches, and how to drive loads such as LED, relays and sounders. We also showed you how to use the Serial Monitor to test and debug your code. In this third part we will be introducing the ESP32's analogue-to-digital converter (ADC) and moving into the analogue world. Our *Teach-In Practical Project* is a tester for 1.5V alkaline batteries.

The learning objectives for this third part of our series are to know how to:

- Configure and use simple analogue I/O
- Interface analogue sensors
- Use binary, octal, hexadecimal and ASCII.

ESP32 analogue input

The ESP32 has two 12-bit analogue-to-digital converters (ADC). Each of these supports up to 18 analogue channels, but not all may be available in a particular development board implementation. For example, the 30-pin board that we're using for most of our practical projects has just six ADC1 channels and nine ADC2 channels available. A further limitation is that ADC2 is unavailable when Wi-Fi is being used. Obviously, this isn't an issue if Wi-Fi isn't required, but it might be a problem if you need many analogue channels. Fig.3.1 shows the ADC pins available on the most common 30- and 36-pin ESP32 boards.

The ESP32 ADC uses a technique known as 'successive approximation'. This uses a comparator that compares an analogue input with the output of a digital-to-analogue converter (DAC), as shown in Fig.3.2. The digital input to the DAC (a 12-bit value) is held in a dedicated successive-approximation register (SAR). This holds a series of values that rapidly approximate to an SAR value that's equivalent to the analogue input. The process stops when the data held in the SAR is converted (by the DAC) to an analogue value perceived by the comparator as being the same as the analogue input.

Gotcha!
The ESP32 supports 18 different analogue channels but not all of them may be present on a particular development board.

About Teach-In
Our latest *Teach-In* series is about using the popular ESP32 module as a basis for learning electronics and coding. We will be making no assumptions about your coding ability or your previous experience of electronics. If you know one but not the other, you have come to the right place. On the other hand, if you happen to be a complete newbie there's no need to worry because the series will take a progressive hands-on approach. There will be plenty of time to build up your knowledge and plenty of opportunity to test things out along the way.

We've not included too much basic theory because this can be easily found elsewhere, including several of our previous *Teach-In* series, see:

https://bit.ly/pe-ti
https://bit.ly/pe-ti-bundle

Earch month, there'll be projects and challenges to help you check and develop your understanding of the topics covered.

Reading analogue inputs

Last month, we used `digitalRead()` to sense the state of the ESP32's GPIO pins, the result being either HIGH or LOW. The corresponding function for analogue inputs is `analogRead()`.

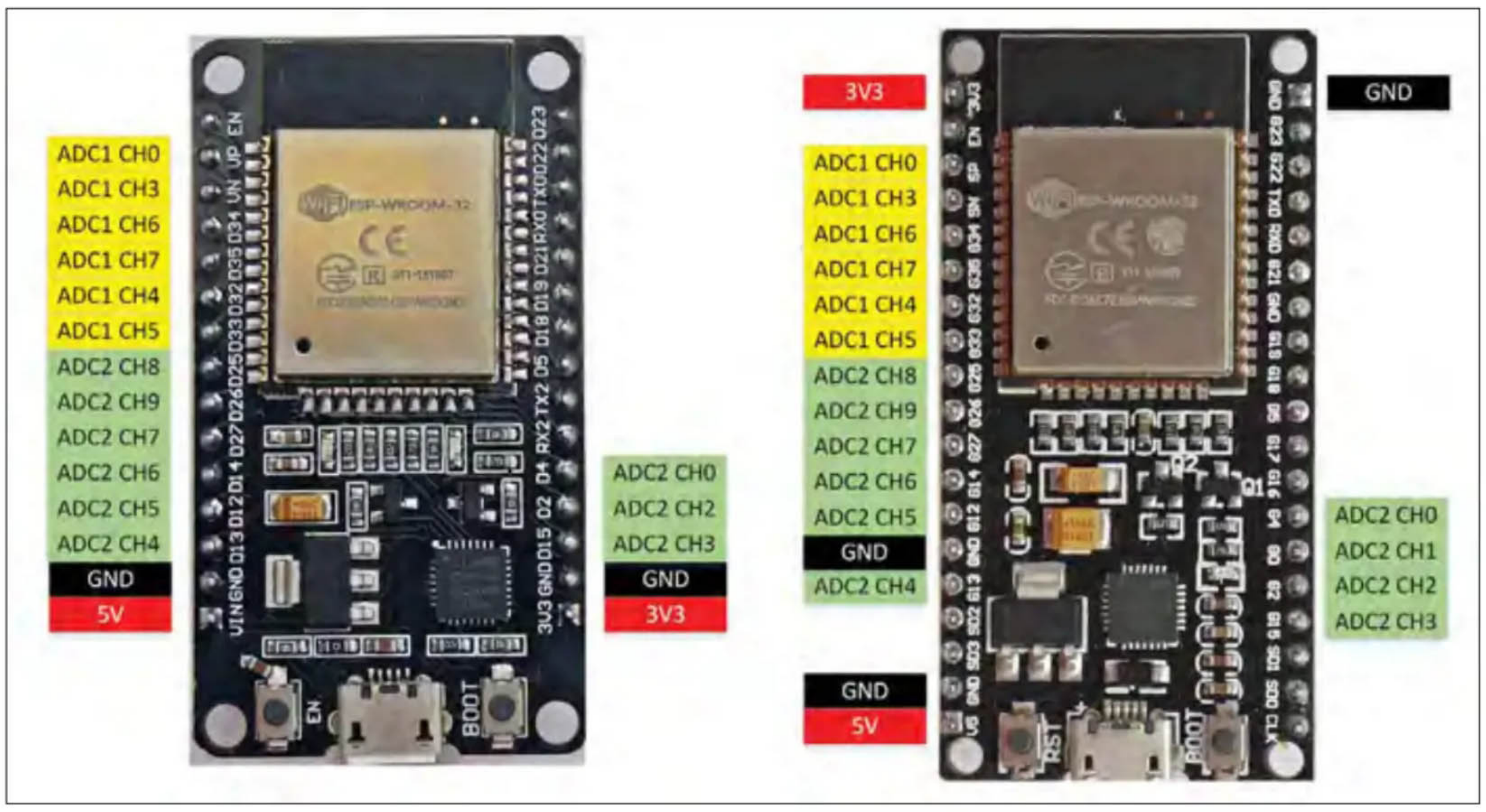


Fig.3.1. Analogue pins on two common ESP32 development boards (30-pin left/36-pin right).

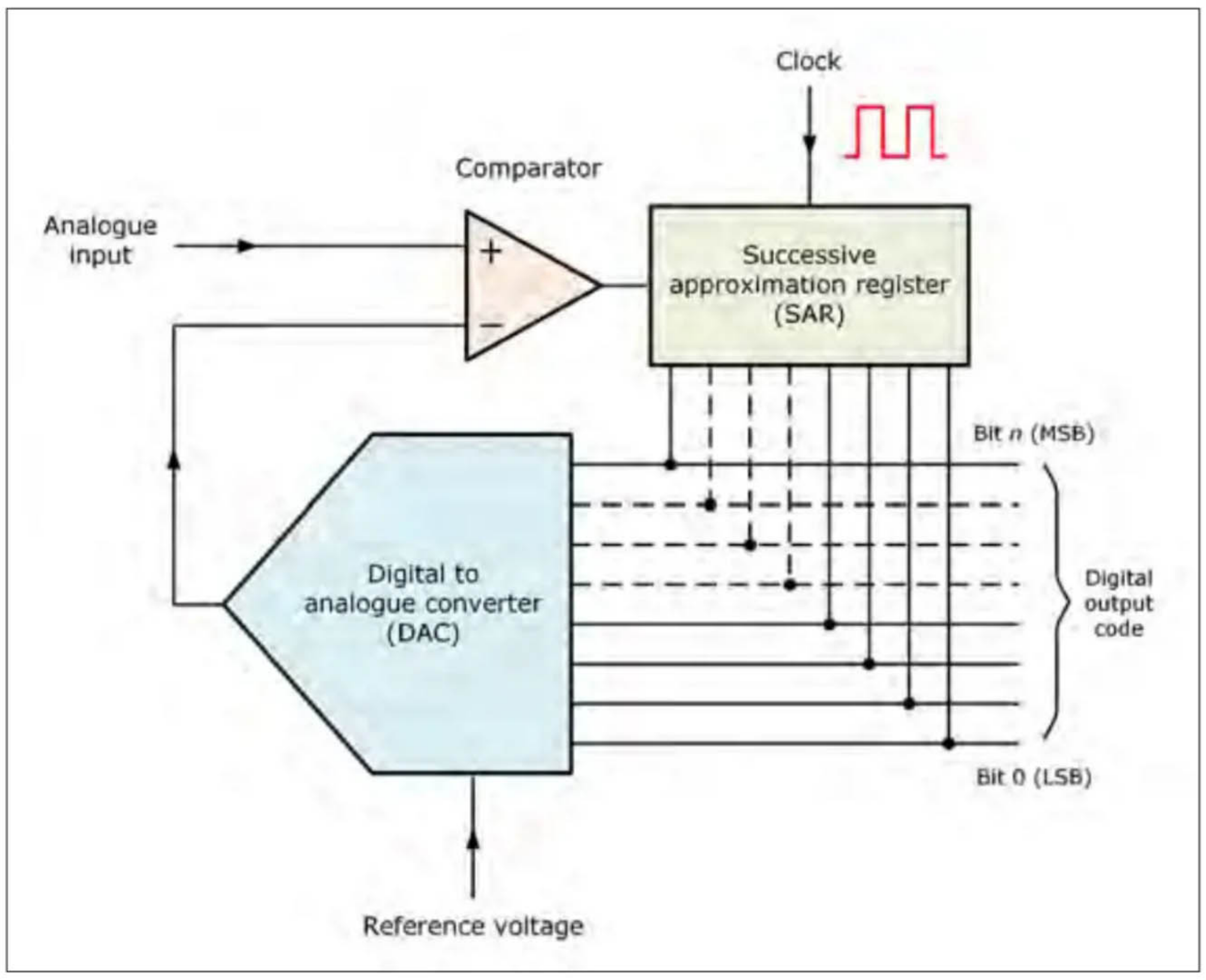

Clock
Comparator
Analogue input
+
–
Successive approximation register (SAR)
Bit n (MSB)
Digital to analogue converter (DAC)
Digital output code
Bit 0 (LSB)
Reference voltage

Fig.3.2. An ADC based on successive approximation.

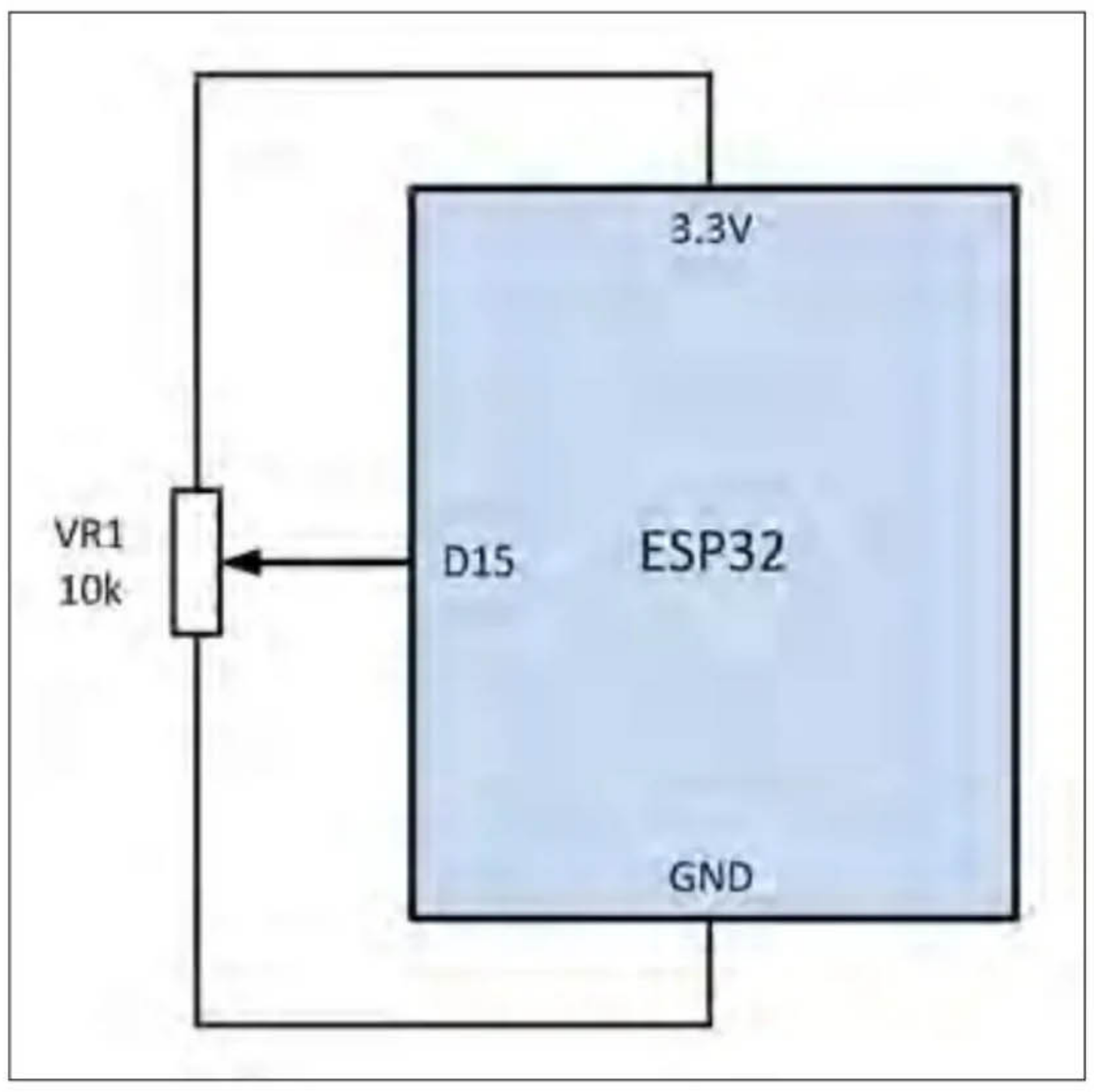

3.3V
VR1
10k
D15
ESP32
GND

Fig.3.3. Using a potentiometer to test the ADC.

Gotcha!

ADC2 can't be used if your application is using Wi-Fi. So, if you do need Wi-Fi it's important to use ADC1 instead.

As you might expect, `analogRead()` requires a GPIO pin as an argument. Note that we would normally want to assign the pin before the main body of code using a statement like this:

```
int analogPin = 15;   // Sensor voltage on pin-15
```

Here, GPIO15 (often marked 'D15' on development boards) corresponds to ADC2 Channel 3. Later in the code we will need a variable in which to store the returned analogue value from pin-15. We can do this using:

```
int  rawReading  =  analogRead(analogPin);  //
Sensor value
```

The result stored in `rawReading` will be a 12-bit value from the ADC. This can range from 0 to 4095 (where 4095 corresponds to the 3.3V DAC reference voltage).

In some applications you might need to convert the 12-bit value from the ADC into a corresponding voltage value. To do this, you will need to convert the value returned by the ADC and store it in a `float` variable, as in:

```
Float  volts  =  rawReading  *  (3.3/4095);   //
Convert to voltage
```

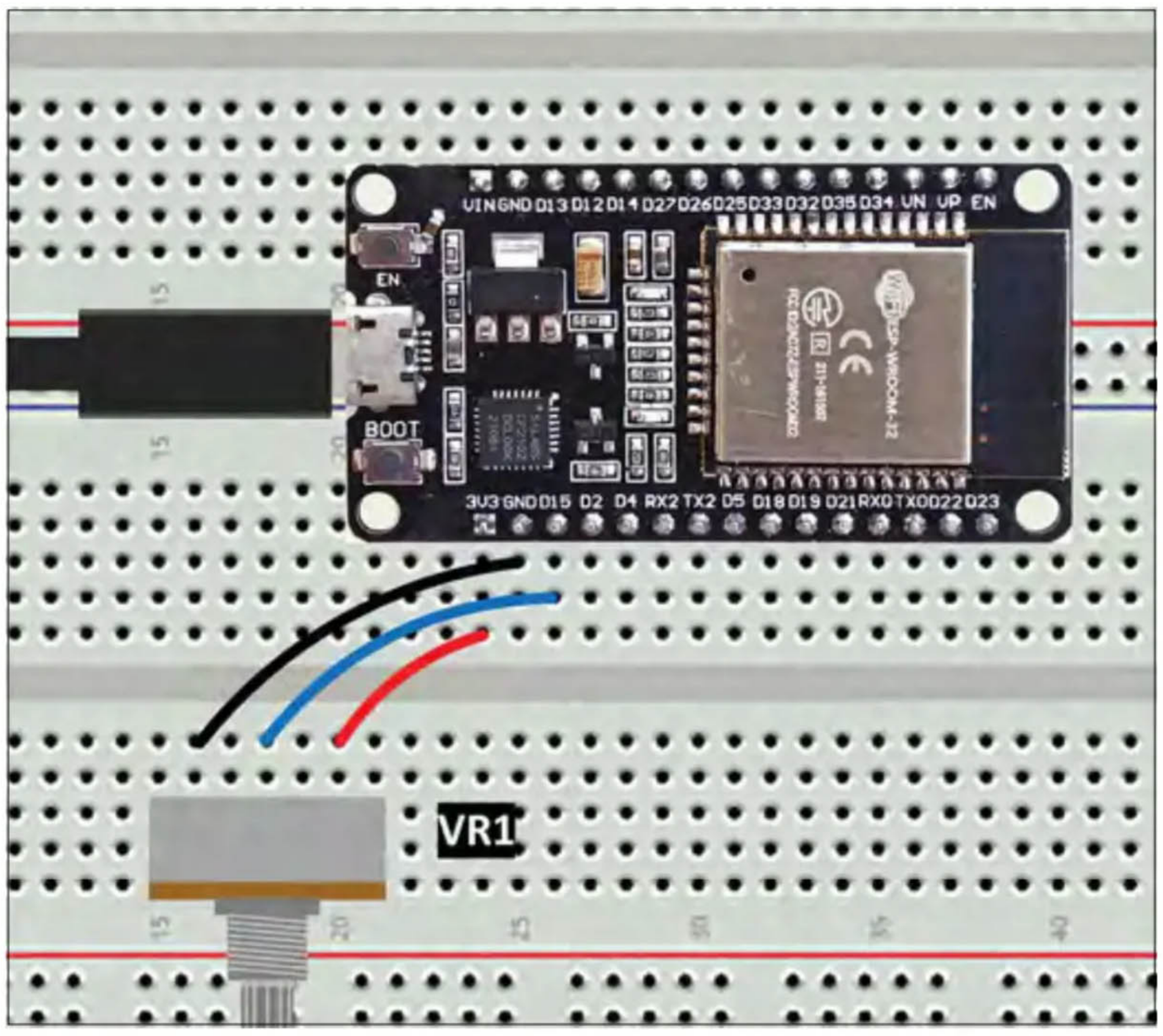


Fig.3.4. Wiring arrangement for the circuit shown in Fig.3.3.

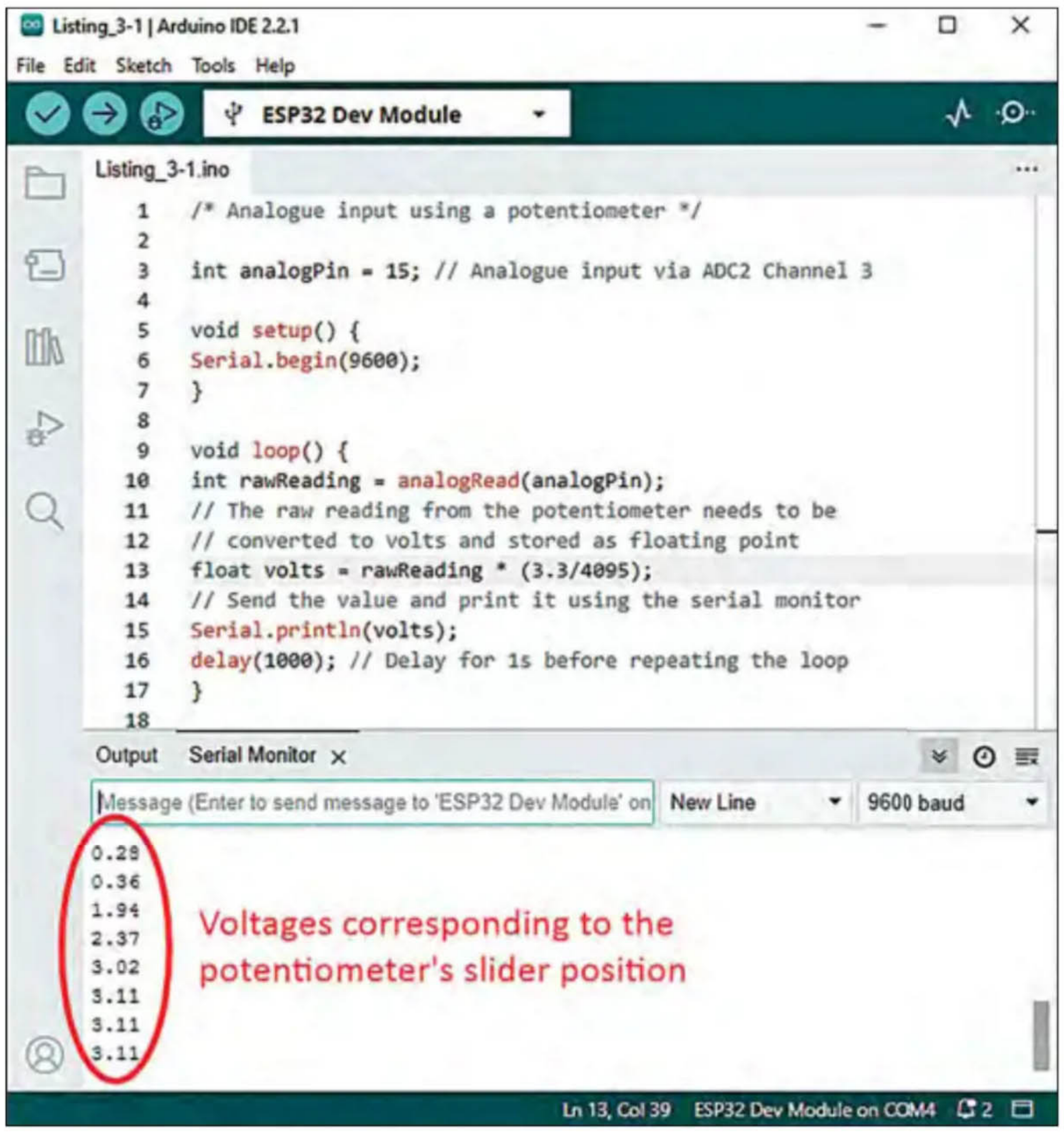
There are two things to note from this. First, we need to use a `float` because we are no longer dealing with integer values for voltage.

Second, a scaling factor (3.3/4095) is needed to convert our raw reading from the ADC into a corresponding voltage.

It's worth checking this out by connecting an ordinary potentiometer (10kΩ to 20kΩ would be ideal) across the 3.3V supply with the slider taken to the pin in question, as shown in Fig.3.3. A suggested wiring arrangement is shown in Fig.3.4.

Enter or download the code shown in Listing 3.1 – all this month's code is available for download from the May 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

When you execute the code and start the Serial Monitor you will see the voltage present at pin-15 updated every second. If you rotate the shaft of the potentiometer over its full range, you will see the voltage changing smoothly from 0V at one extreme to 3.3V at the other. Typical analogue readings are shown in Fig.3.5.


Listing_3-1 | Arduino IDE 2.2.1
File Edit Sketch Tools Help
ESP32 Dev Module
Listing_3-1.ino
Output
Serial Monitor
Message (Enter to send message to 'ESP32 Dev Module' on
New Line
9600 baud
Ln 13, Col 39 ESP32 Dev Module on COM4

```
/* Analogue input using a potentiometer */

int analogPin = 15; // Analogue input via ADC2 Channel 3

void setup() {
Serial.begin(9600);
}

void loop() {
int rawReading = analogRead(analogPin);
// The raw reading from the potentiometer needs to be
// converted to volts and stored as floating point
float volts = rawReading * (3.3/4095);
// Send the value and print it using the serial monitor
Serial.println(volts);
delay(1000); // Delay for 1s before repeating the loop
}
```

```
0.28
0.36
1.94
2.37
3.02
3.11
3.11
3.11
```

Voltages corresponding to the potentiometer's slider position

Fig.3.5. Typical analogue readings obtained from the Serial Monitor.

Gotcha!

The ESP32's ADC are non-linear at both extremes. It's important to be aware that input voltages below 0.1V will be read as 0V, while inputs above 3.2V will be read as 3.2V. If you can live with these restrictions, then it's worth noting that the device is reasonably linear from 0.5V to 2.5V.

Gotcha!

Voltages outside the range 0 to 3.3V must never be applied to the ESP32's analogue input pins. If you need to measure larger voltages it will be necessary to use a potential divider at the input. Furthermore, in some applications it's important to avoid reverse polarity at the input.

Listing 3.1 Testing the ADC with a potentiometer

```
/* Analogue input using a potentiometer */

int analogPin = 15; // Analogue input via ADC2 Channel 3

void setup() {
Serial.begin(9600);
}

void loop() {
int rawReading = analogRead(analogPin);
// The raw reading from the potentiometer needs to be
// converted to volts and stored as floating point
float volts = rawReading * (3.3/4095);
// Send the value and print it using the serial monitor
Serial.println(volts);
delay(1000); // Delay for 1s before repeating the loop
}
```

Listing 3.2 Using the serial plotter

```
// Using the serial plotter
void setup() {
   // Start serial communication at 9600 bps
   Serial.begin(9600);
}

void loop() {
   // Select ADC2 Channel 3 (GPIO pin-15)
   int gpioPin = 15;
   // Read the voltage at D15
   int analogVolts = analogReadMilliVolts(gpioPin);
   // Display the current voltage in mV
   Serial.printf(“ADC input = %d mV\n”,analogVolts);
   // Wait for a while
   delay(1000);
}
```

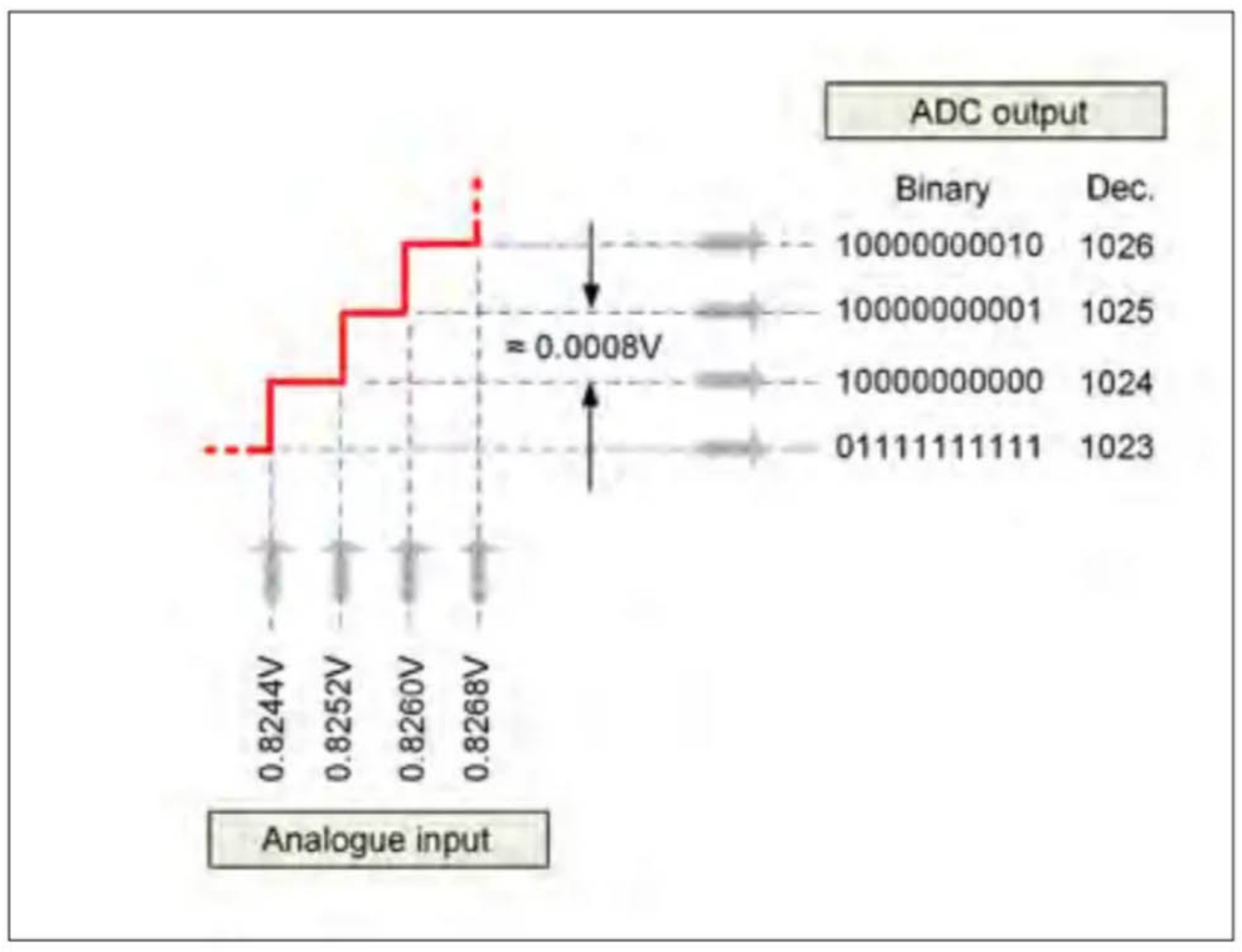


Fig.3.6. The ESP32's ADC step size.

ESP32 ADC performance

Before we move on to some practical ESP32 ADC applications it's worth explaining some of the specifications and potential limitations of the device.

Resolution

The resolution of an ADC is defined by its step size. In the ESP32, a 3.3V supply reference is used with a 12-bit ADC. This achieves a comfortably small step size of approximately 0.8mV (3.3/4096). This step size is illustrated in Fig.3.6. If you don't need the full default 12-bit resolution you can select a different value using `analogReadResolution()`. For example, 10-bit resolution (2^{10} = 1024 different values) can be selected using `analogReadResolution(10)`.

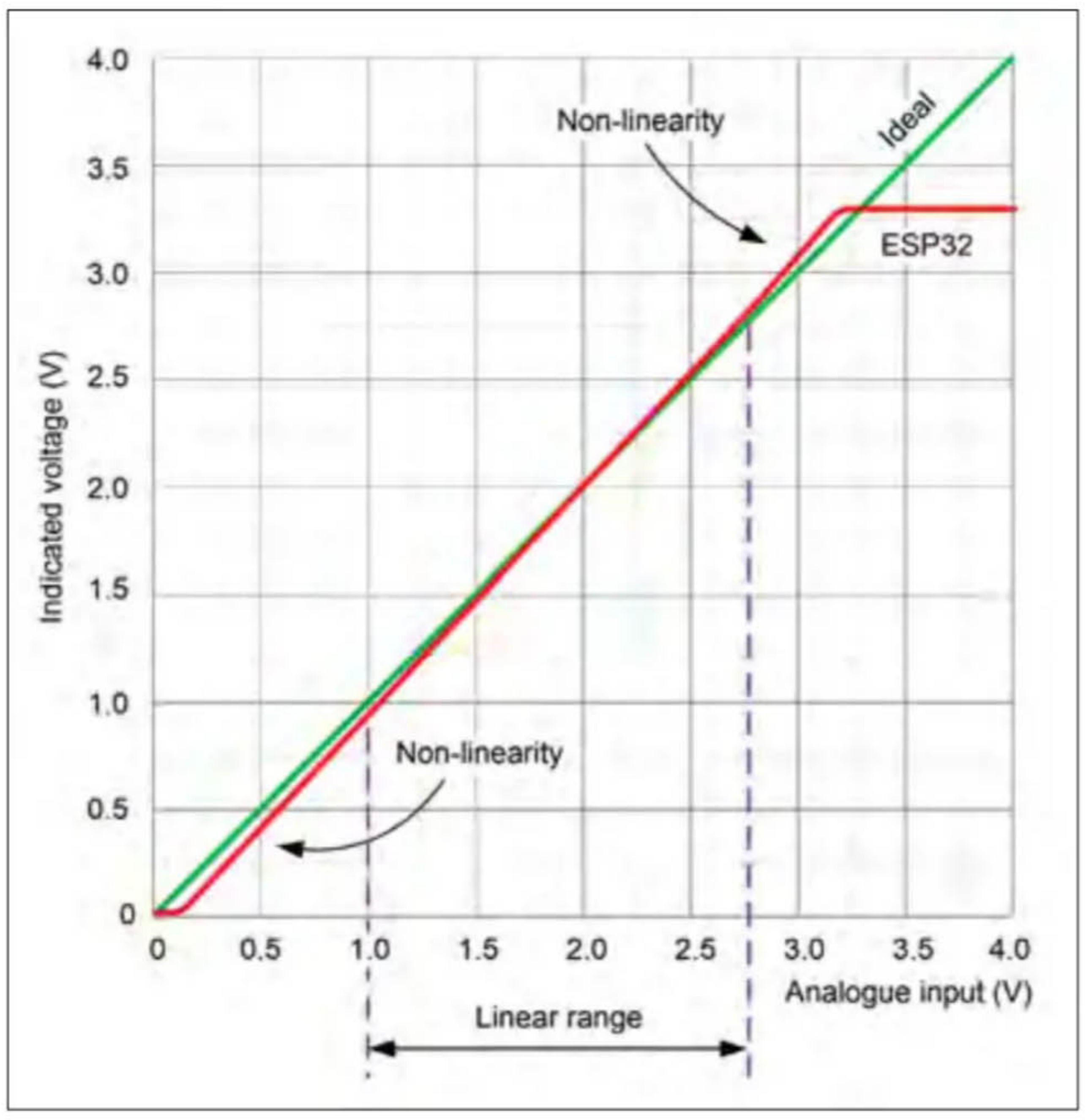


Fig.3.7. ESP32 ADC non-linearity (the range from 1V to 2.75V can be considered reasonably linear).

Accuracy

The accuracy of an ADC depends on the accuracy of its reference voltage source. The reference voltage for the ESP32 is derived from the 3.3V supply and there's no provision for an external (and more accurate) reference voltage source.

Linearity

Ideally, an ADC should be perfectly linear. Unfortunately, an uncomfortable peculiarity of the ESP32's ADC is that it does exhibit some non-linearity, as shown in Fig.3.7.

Range

The ESP32's analogue input range extends from 0V to 3.3V. The voltage applied must not be allowed to fall outside this range.

Introducing the Serial Plotter

Thus far in our series we've made extensive use of the IDE's Serial Monitor,

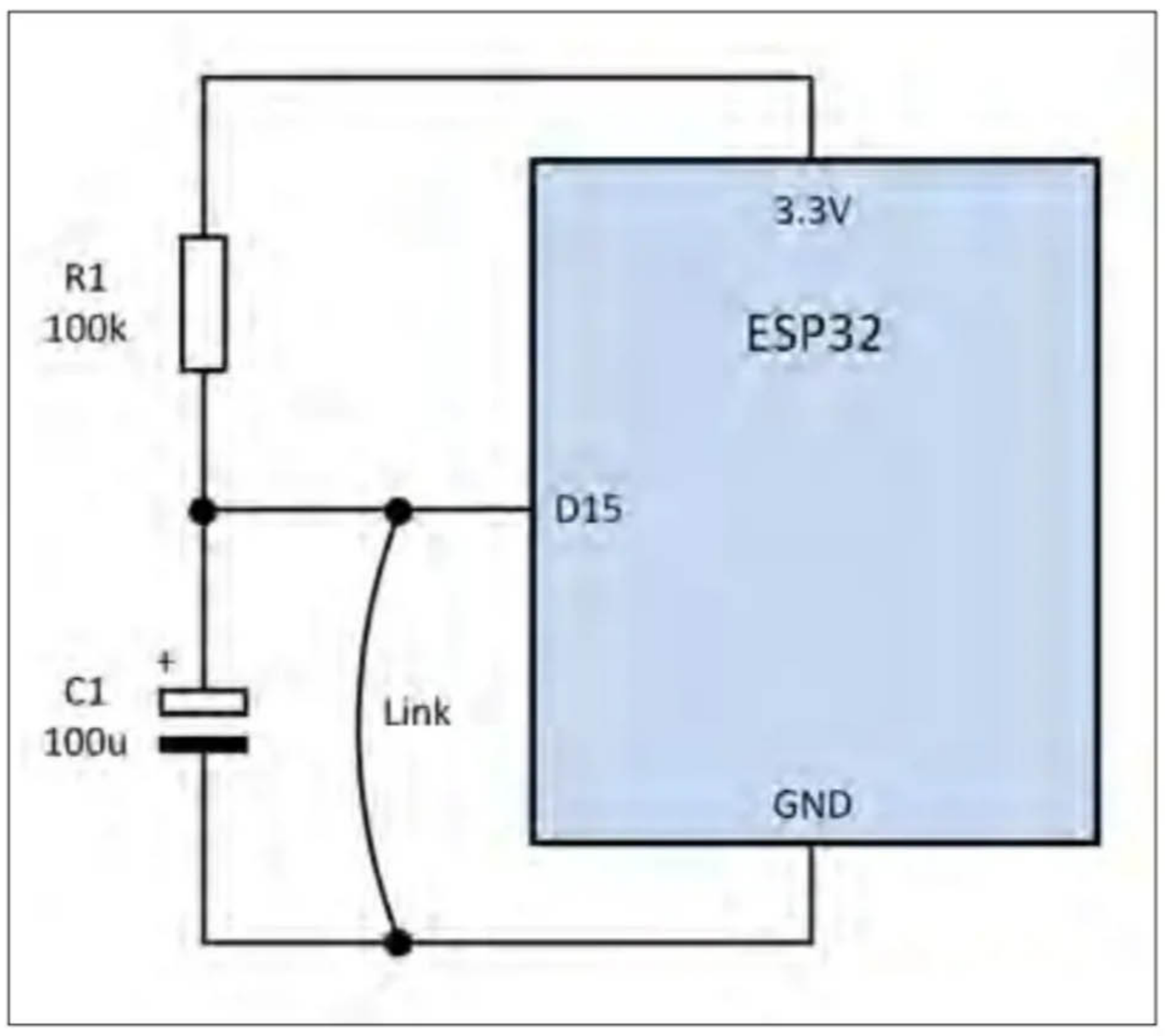


Fig.3.8. Circuit to demonstrate the use of the Serial Plotter.

Listing 3.3 LDR test code

```
/* Simple LDR analogue interface */
int analogPin = 15; // Use ADC2 Channel 3

void setup() {
Serial.begin(9600);
}

void loop() {
// Get the current input from the LDR
int ldrValue = analogRead(analogPin);
Serial.println(ldrValue);
delay(1000);
// Repeat forever
}
```

but there's another useful tool that's worth knowing about. This is the Serial Plotter, which will provide you with a neat way of visualising data that changes over time. We'll now use the Serial Plotter to show how the voltage across a capacitor increases as it charges. The code is shown in Listing 3.2, the circuit in Fig.3.8, and a suggested wiring diagram is illustrated in Fig.3.9. When running Listing 3.2 you will need to start execution with the shorting link in place see Fig.3.8.)

After the code in Listing 3.2 has been compiled and uploaded, select Tools from the IDE's menu bar and then Serial Plotter. Next, remove the shorting link so that the capacitor begins to charge. You should observe a Serial Plotter display like that shown in Fig.3.10. After the capacitor has fully charged (ie, when the voltage at D15 has reached and flattened off at 3.3V) replace the link and repeat the measurement with different values for C1 and R1 (try 10µF, 47µF and 220µF). Note how this affects the charging rate. C-R circuits are widely used in electronics, as we will see a little later when we need to average a voltage over a period of time.

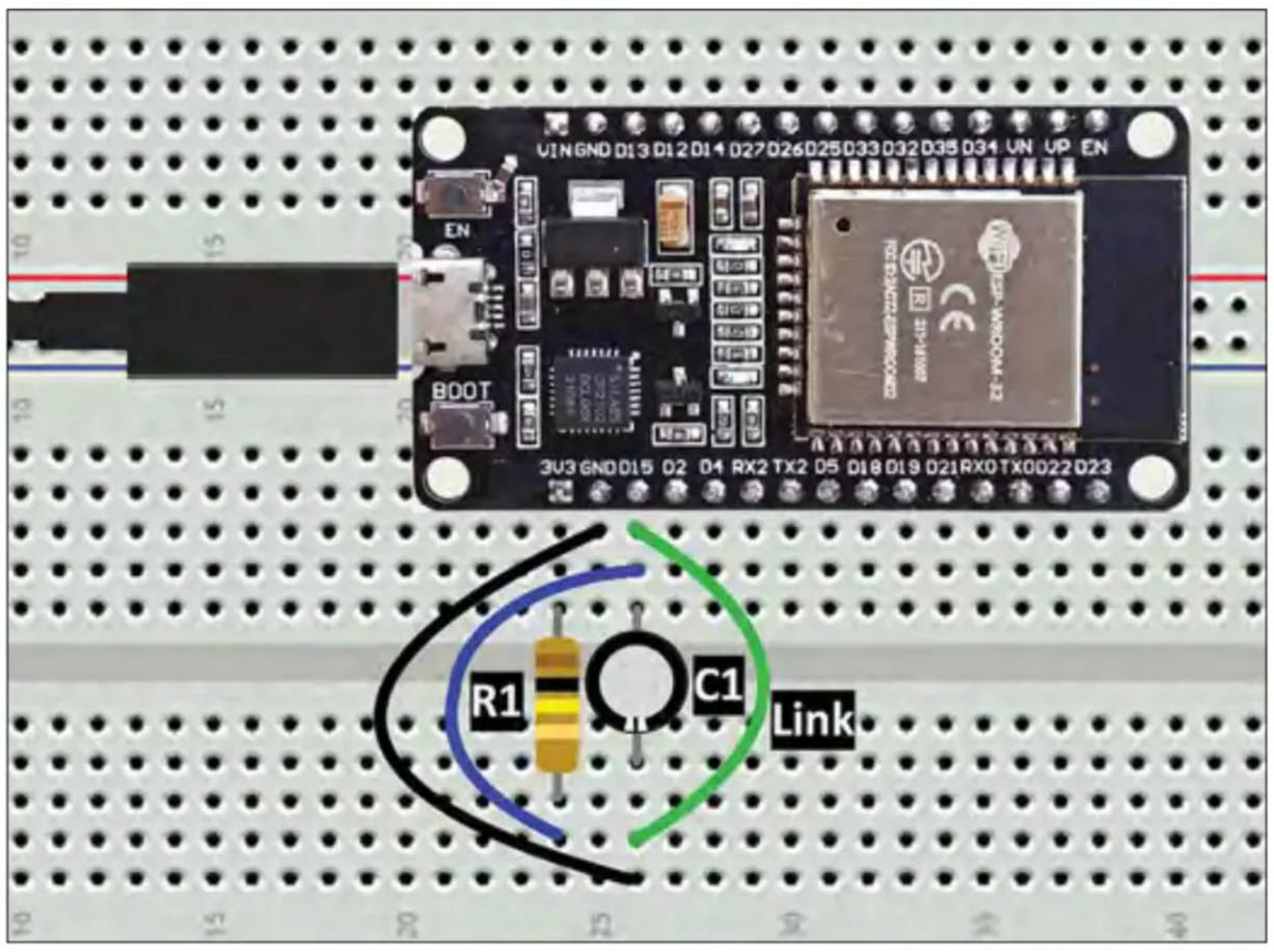


Fig.3.9. Suggested wiring layout for Fig.3.8.

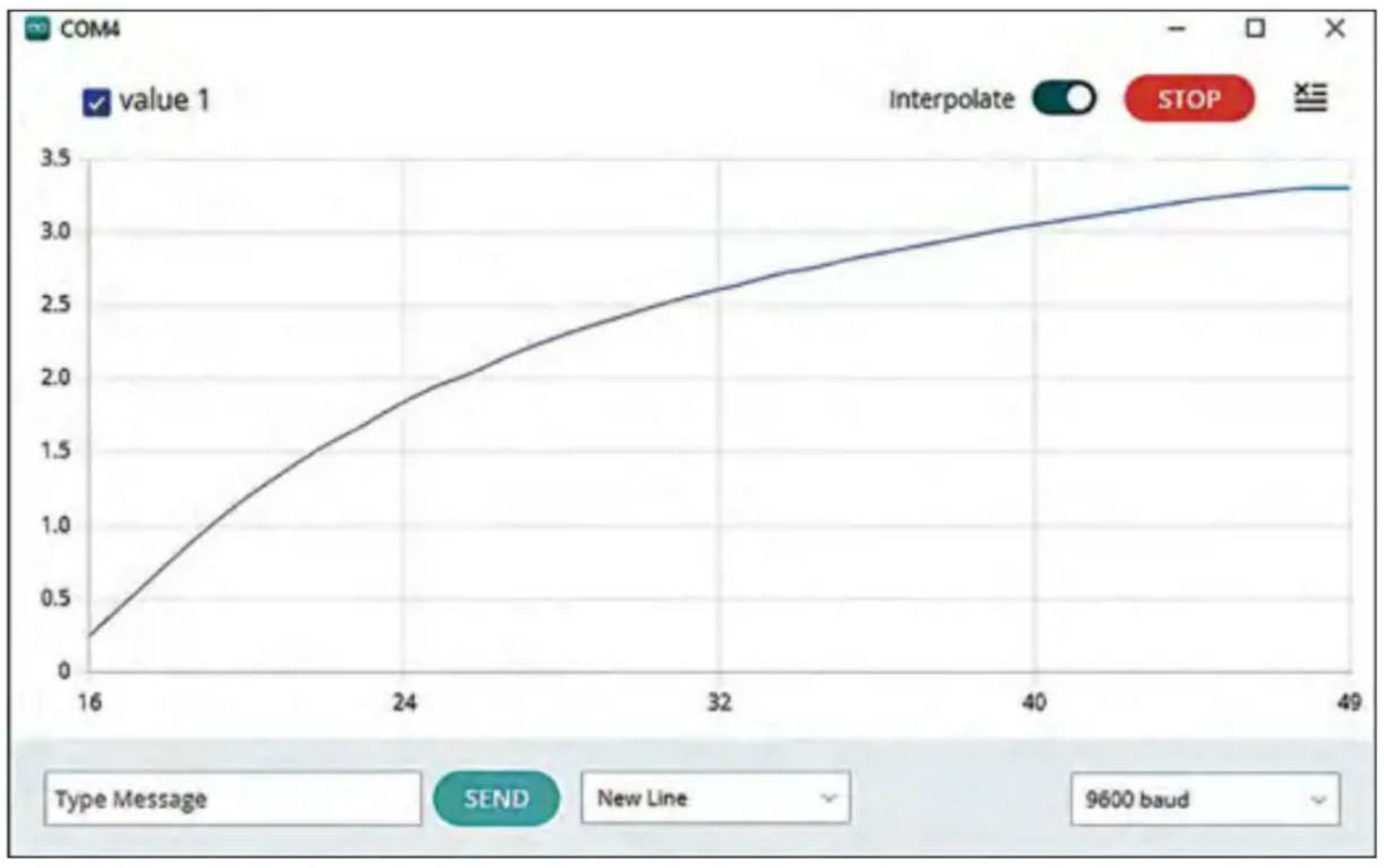


Fig.3.10. Serial Plotter display for Listing 3.2.

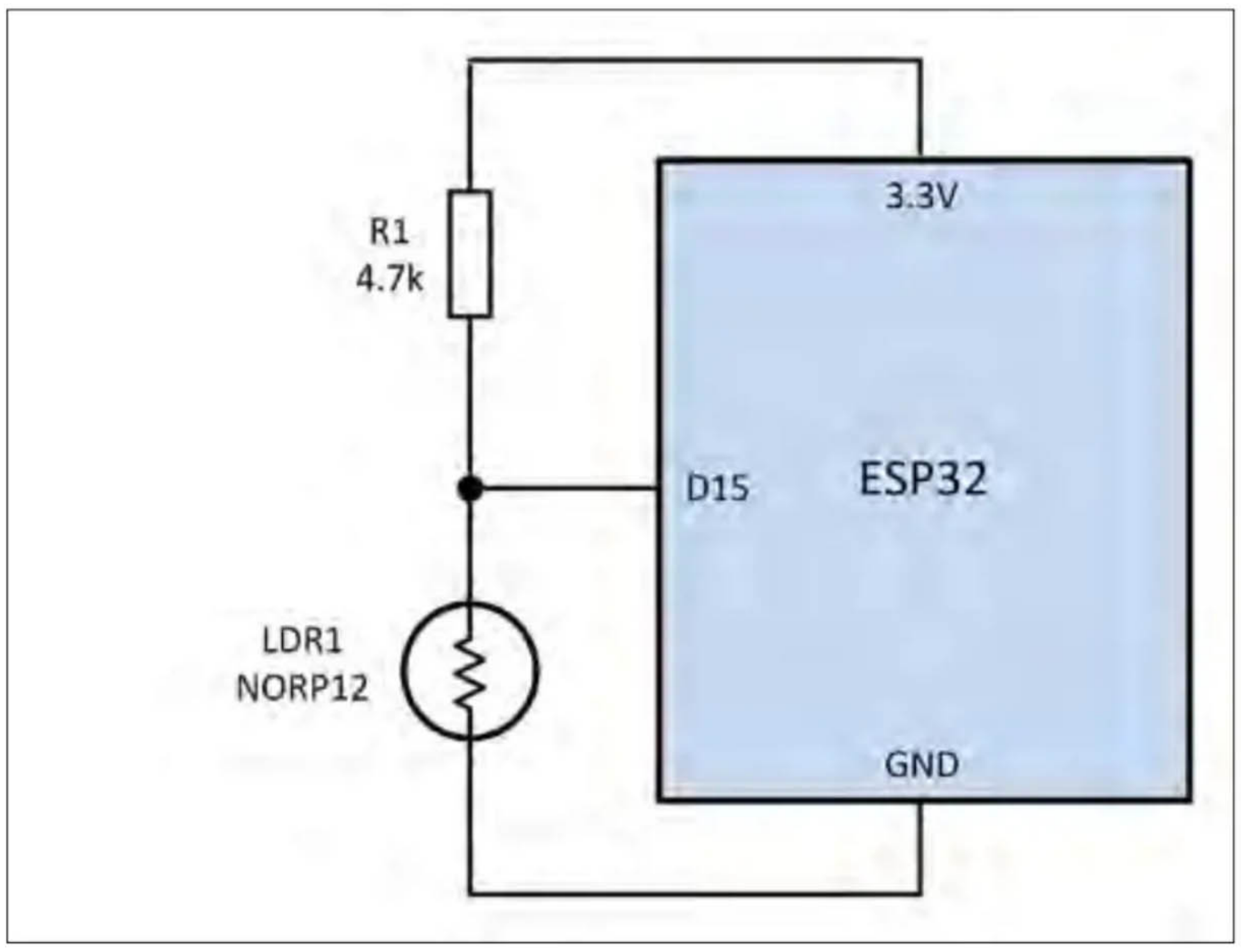


Fig.3.11. Simple LDR interface.

Interfacing analogue sensors

The ESP32's analogue inputs provide you with a means of interfacing a variety of simple, low-cost analogue sensors. As an example, we will show you how to sense ambient light level using a light-dependent resistor (LDR).

Interfacing analogue sensors with the ESP32 is usually very straightforward, as we will now show using an LDR. Most LDRs exhibit resistances of several megohms in total darkness falling progressively to a few hundred ohms in bright sunlight. Since the ESP32 can't sense resistance directly, this resistance change needs to be converted to a corresponding change in voltage. This is easily done by connecting a series resistor to supply current to the LDR. The voltage dropped across the LDR will then be inversely proportional to incident light. This voltage can then be passed to an analogue input for sensing.

A simple arrangement for light sensing is shown in Fig.3.11 with R1 and LDR1 forming a potential divider across the 3.3V supply. The level of ambient light can be displayed using the Serial Monitor using the code shown in Listing 3.3. Once again, we've used ADC2 Channel 3 and GPIO pin D15. A suggested wiring diagram is shown in Fig.3.12.

If you execute the code shown in Listing 3.3 you will be rewarded with values that decrease as the intensity of incident light increases. Our readings varied from as low as 200 in strong sunlight to 4095 in full darkness. Average room lighting produced a value of around 2200.

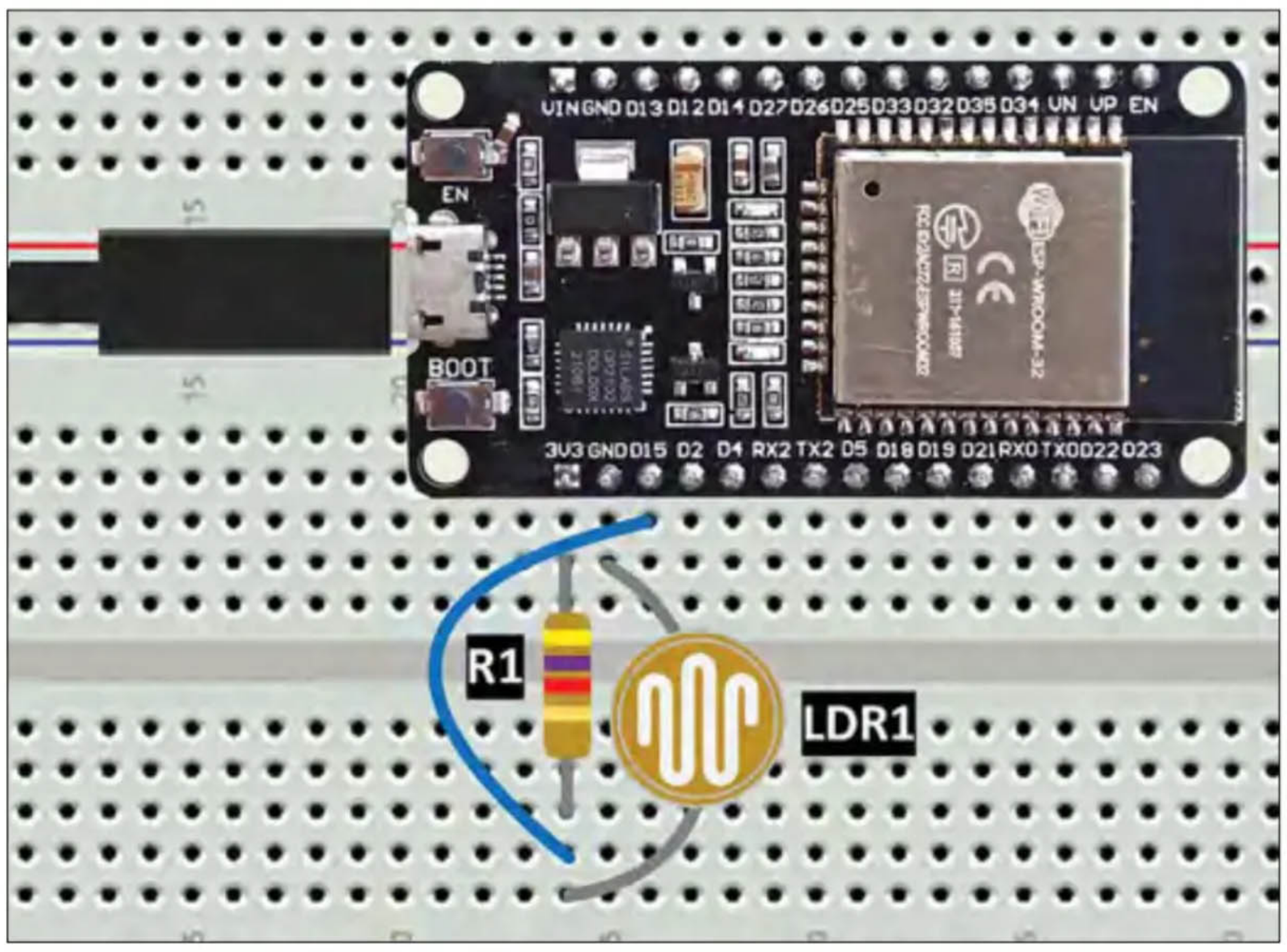


Fig.3.12. Suggested wiring diagram for Fig.3.11.

Listing 3.4 Code for the automatic light controller

```
/* Simple analogue LDR lighting controller using a relay.
NB: The relay interface is active ‘low’ so a LOW output will
turn the load ‘on’ while a HIGH output will turn it ‘off’.
*/

int ldrPin = 15;            // Analogue input via ADC2 Channel 3
int relayPin = 4;           // Digital output via GPIO 4
int thresholdValue = 2000;  // Set darkness threshold

void setup() {
   pinMode(relayPin, OUTPUT); // Set the relay as an output
   digitalWrite(relayPin, HIGH);    // Start with light ‘off’
}

void loop() {
   // Get the current analogue input from the LDR
   int ldrValue = analogRead(ldrPin);
   if (ldrValue < thresholdValue)
        digitalWrite(relayPin, HIGH);     // Enough light so switch ‘off’
   else
        digitalWrite(relayPin, LOW);  // Not enough light so switch ‘on’
   delay(1000);                        // 1s delay
   // Repeat forever
}
```

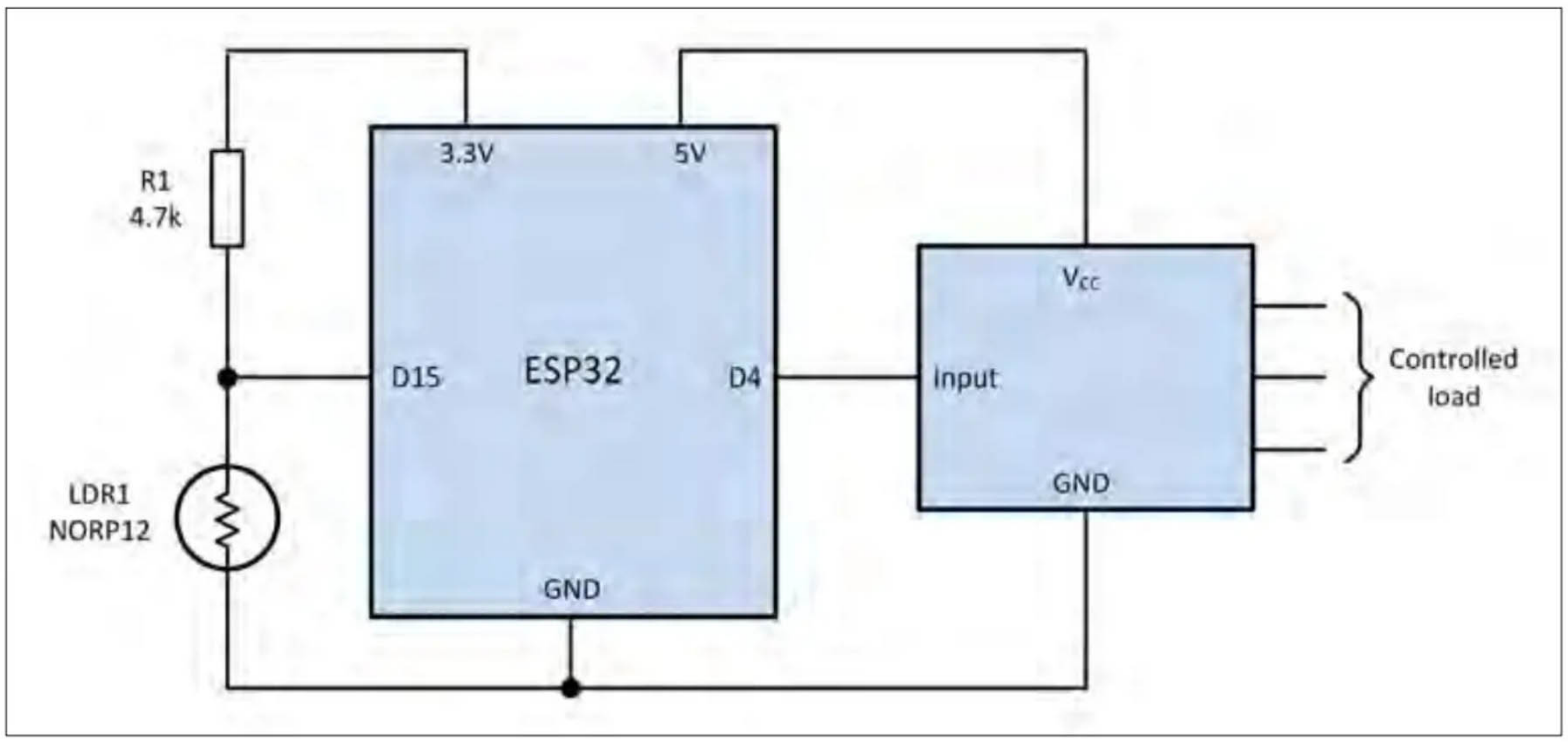


Fig.3.13. Circuit of the automatic light controller.

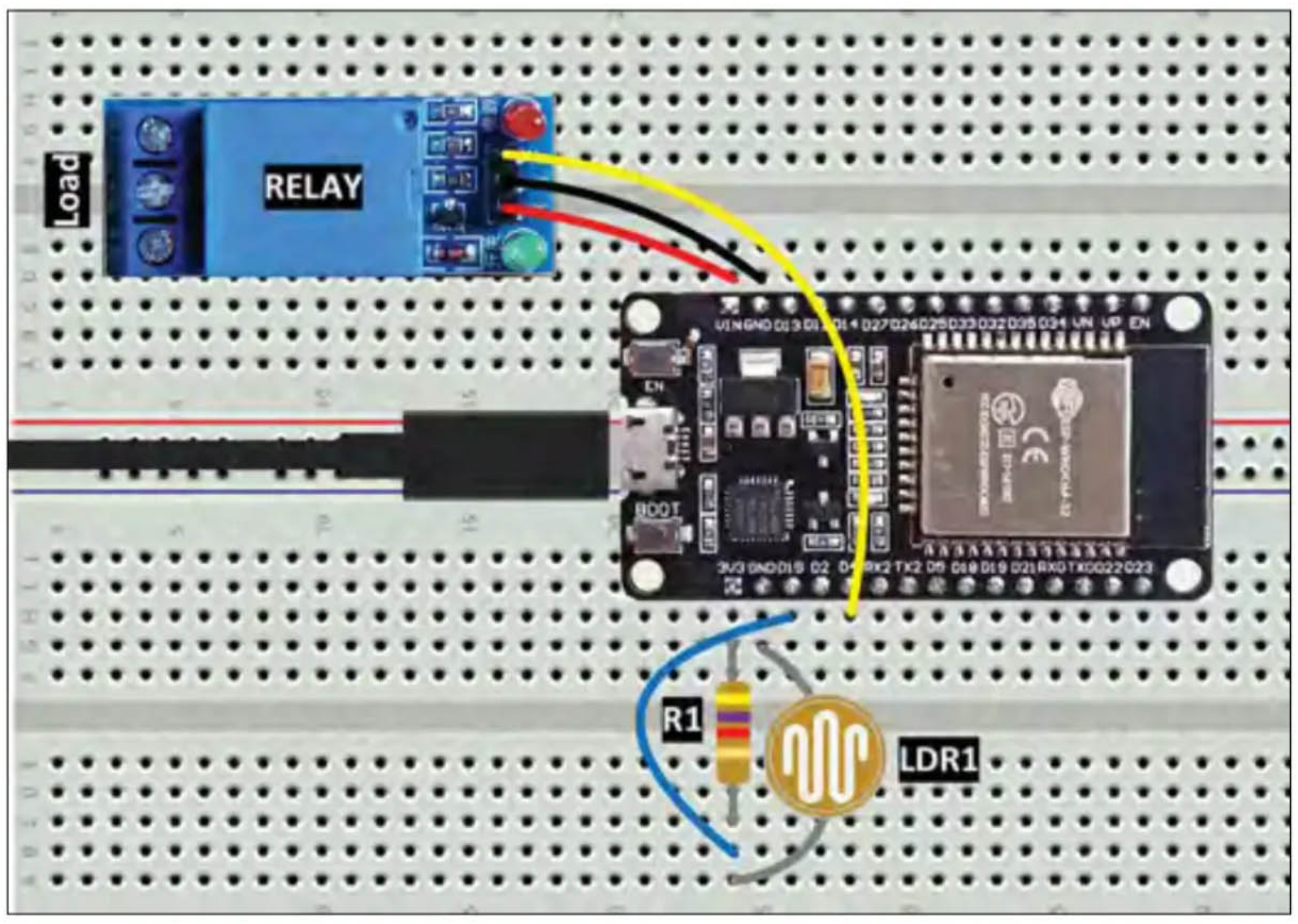


Fig.3.14. A suggested wiring layout for Fig.3.13.

Check it out!

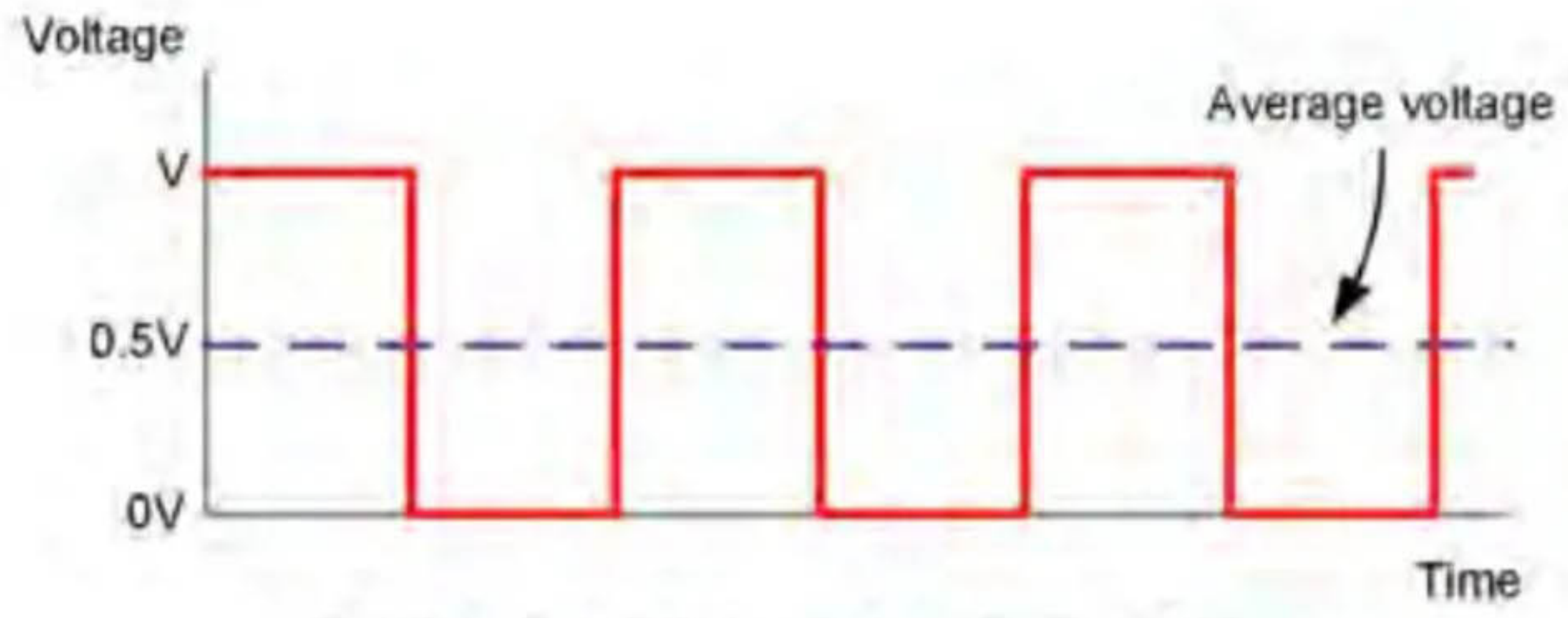
Having demonstrated how easy it is to sense light level using a low-cost LDR it is worth showing how this inexpensive component can form the basis of a simple automatic lighting controller. Fig.3.13 shows the circuit of our automatic light controller. The output of our ESP32 at D4 is fed to a relay interface (see last month). This relay is activated by a LOW state output from D4. A suggested wiring diagram is shown in Fig.3.14. Note that the relay derives it positive supply from the development board’s +5V/V_{IN} pin rather than from the +3.3V pin.

The code for the automatic light controller is shown in Listing 3.4. This has been liberally commented and should be reasonably self-explanatory. Note that we have set the switching threshold to 2000. This is an arbitrary value and can be changed to suit your own situation.

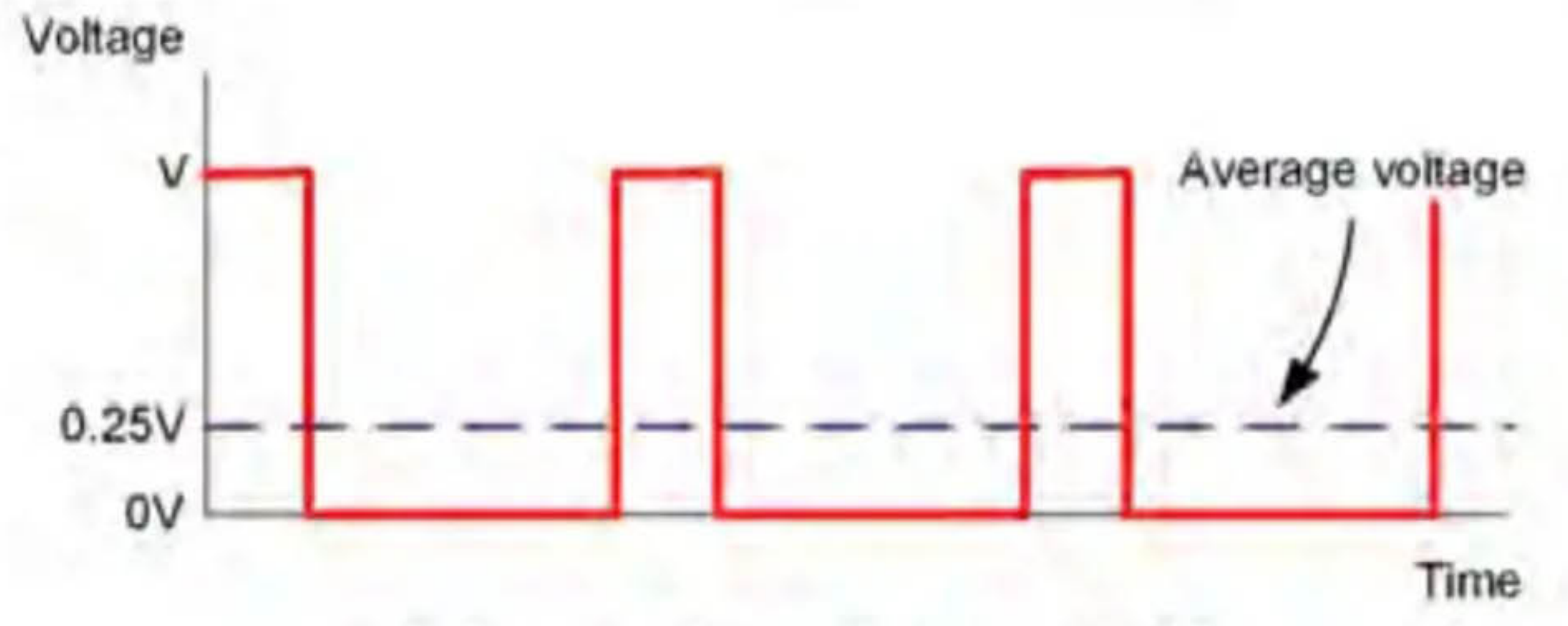
ESP32 analogue output

Having dealt with analogue input, it’s now time to introduce analogue output. Unfortunately, the ESP32 does not incorporate a true digital-to-analogue converter (DAC) so analogue output is based on a technique known as pulse-width modulation (PWM). Because the ESP32 uses PWM the `analogWrite()` function produces a rectangular pulse waveform rather than a continuous analogue voltage. This can be a tricky concept to grasp, so we will take some time to explain how it works.

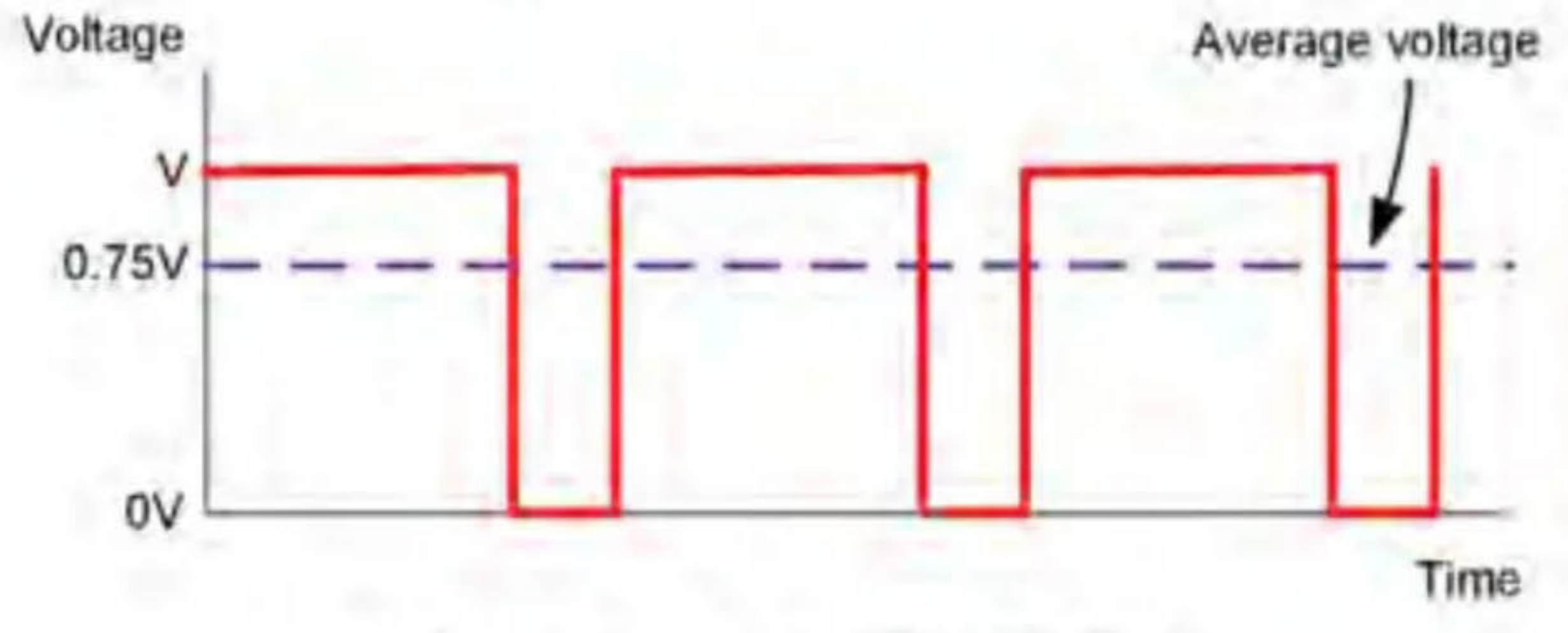
Fig.3.15 shows three different pulse waveforms. At any time, the voltage described by these waveforms can only be either HIGH or LOW. The waveform in Fig.3.15(a) is a perfect square wave and is HIGH for 50% of the time and low for the other 50%. This is equivalent to a mark-space ratio (HIGH-LOW ratio) of 1:1 or a duty cycle of 50%.



(a) Duty cycle: 50%, mark-space-ratio 1:1



(b) Duty cycle: 25%, mark-space-ratio 1:3



(c) Duty cycle: 75%, mark-space-ratio 3:1

Fig.3.15. PWM principle.

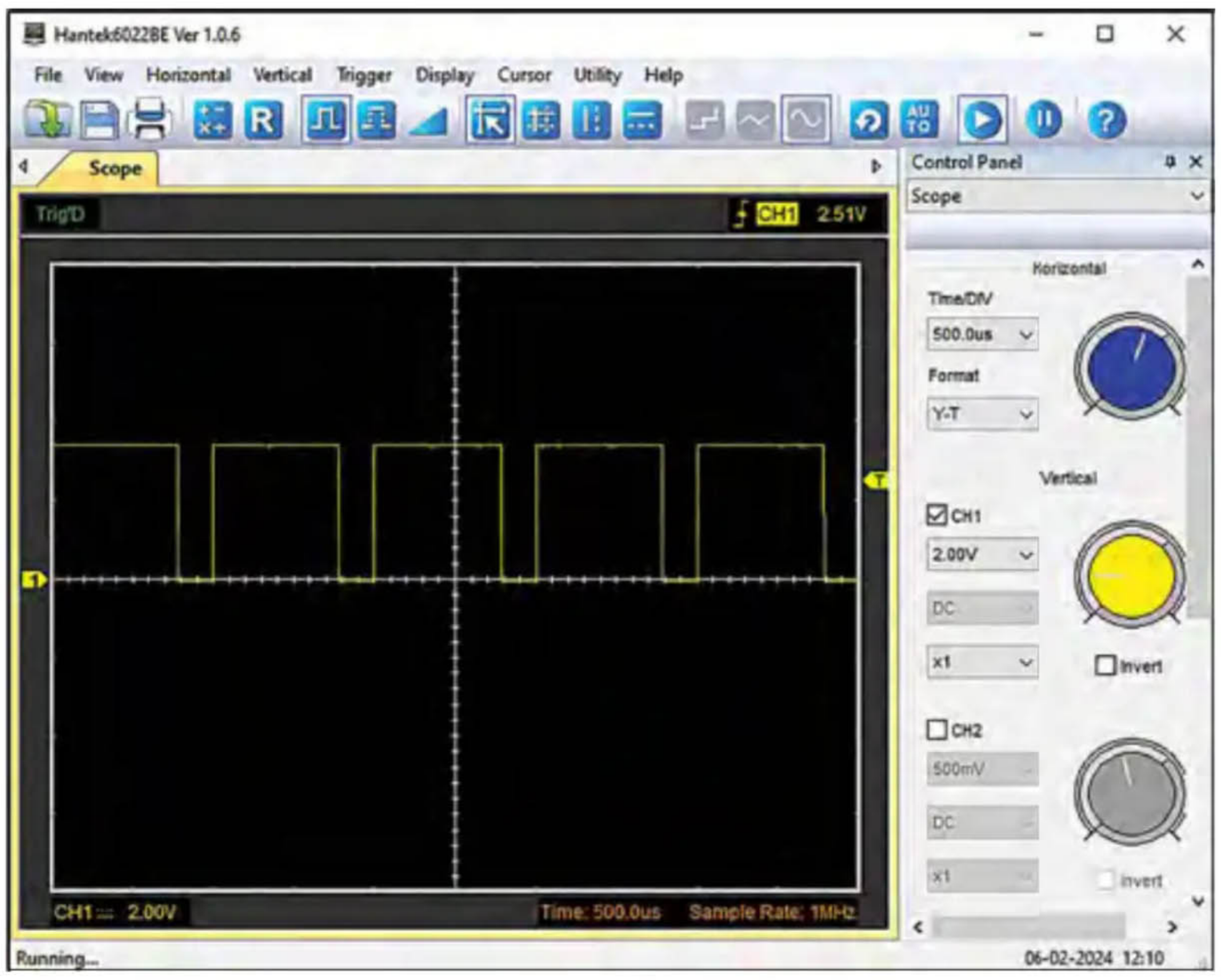


Fig.3.16. PWM output waveform.

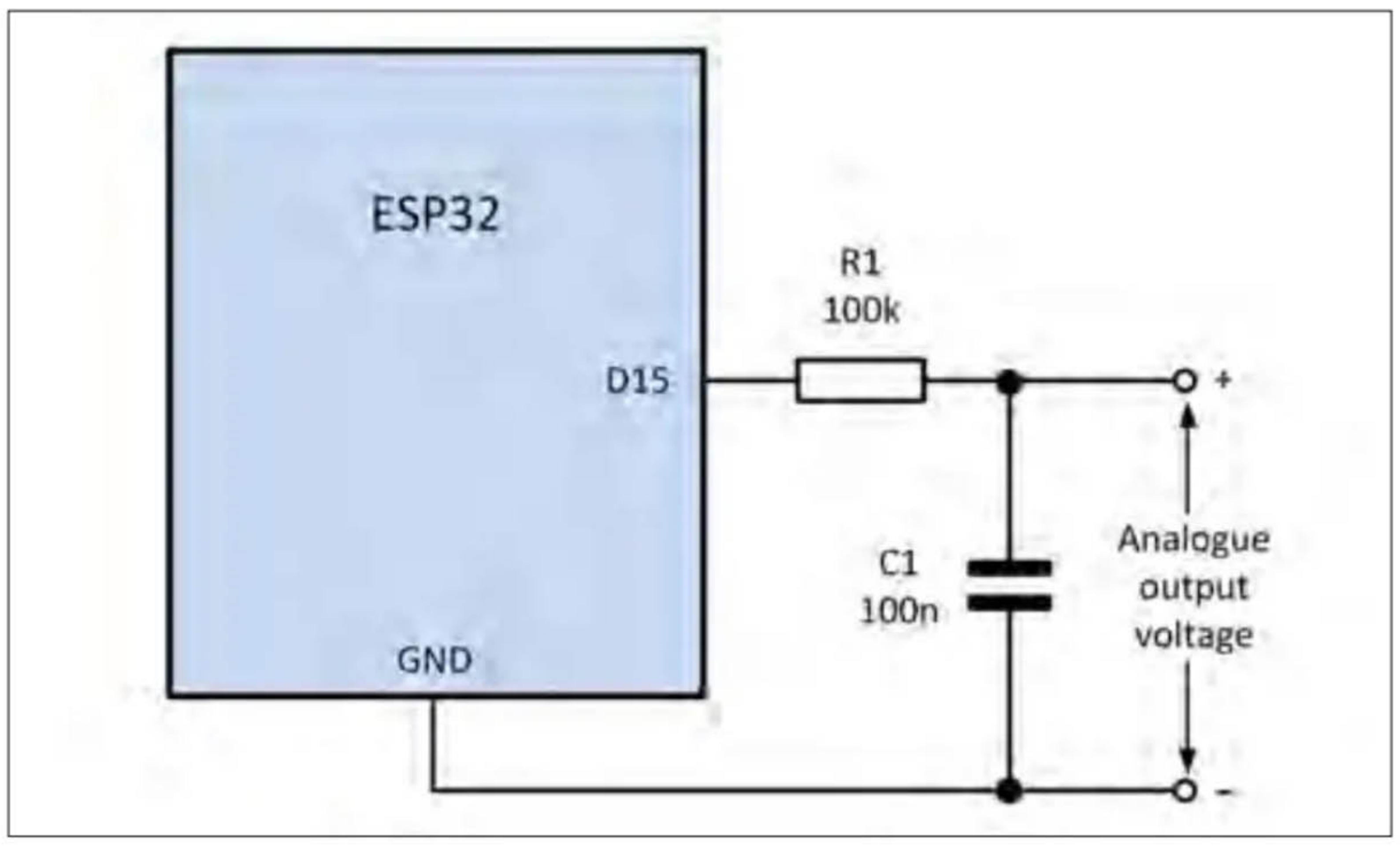


Fig.3.17. Improving the output waveform using a low-pass filter.

The waveform in Fig.3.15(b) is HIGH for 25% of the time and low for the remaining 75%. It has a mark-space-ratio of 1:3. The HIGH time is one quarter of the total time for the cycle and so the duty cycle is 25%.

The waveform in Fig.3.15(c) is HIGH for 75% of the time and low for the remaining 25%. It has a mark-space-ratio of 3:1. The HIGH time is three quarters of the total time for the cycle and so the duty cycle is thus 75%.

Now look again at the three waveforms in Fig.3.15 and note how the *average* value of voltage differs according to the duty cycle. In Fig.3.15(a) the average value is 0.5V where V is the maximum value. The corresponding averages for Figs.3.15(b) and 3.15(c) are 0.25V and 0.75V. Thus, as we change the duty cycle of the wave we also change its average value.

The first of the two parameters used in the `analogWrite()` function is the GPIO pin number, while the second relates to the duty cycle of the waveform. By default, this parameter can range from 0 to 255, corresponding to duty cycles from zero to 100%. So, for example, to generate a 50% duty cycle waveform at D15 we could use lines of the form:

```
int outPin = 15;  // PWM output pin
```

and

```
analogWrite(outPin, 128);  // Output 1.65V
```

Note that 1.65V is 50% of the 3.3V reference voltage. As a further example, let's assume that we need to produce an output of 2.64V. We can determine the value to use for the duty cycle parameter from (2.64/3.3) × 255 = 200 so the code required is:

```
analogWrite(outPin, 200);  // Output 2.64V
```

Fig.3.16 shows the output waveform produced when this function is executed. Note that the pulsed output is not constant (as with a true analogue signal).

You can also define a custom range of duty cycle values. If we need 10-bit instead of 8-bit resolution we can use:

```
analogWrite(outPin, 511, 1023); // Output 1.65V
```

The default PWM frequency for the analogue channels is 5kHz but this can be changed if required. To set the frequency to 10kHz you could use:

```
analogWriteFrequency(10000); //
```

Generating waveforms

Let's now move on to generating a waveform rather than a steady average. This is a little bit trickier because we will need to code the waveform into a repetitive loop in which successive values of duty cycle are output via the DAC. Listing 3.5 shows an example of generating a stepped waveform:

If you enter and execute the code in Listing 3.5 and connect a DC voltmeter between pin-15 and ground you should be rewarded with series of voltage values that steadily increment from zero to about 2.9V in increments of about 0.32V. This is a simple low-speed stepped waveform. You might now be wondering if it's possible to generate a sinewave so let's examine

Listing 3.5 Code for generating a stepped output voltage

```
/* Simple application to produce a stepped output
Using the default ult PWM setting (5kHz) */

int outPin = 15;  // Use GPIO D15

void setup() {
}

void loop() {
   for (int step = 0; step < 10; step++) {
     analogWrite(outPin, step * 25);
     delay(2000);  // 2 sec. delay between levels
   }
}
```

Listing 3.6 Code for sinewave generation using a look-up table

```
/* Low frequency sine wave generator.
This code uses the default PWM settings. */

int outPin = 15;  // Use GPIO D15
// This is the sinewave lookup table:
const uint8_t sineLUT[] = {
   128, 152, 176, 198, 218, 234, 245, 253,
   255, 253, 245, 234, 218, 198, 176, 152,
   128, 103, 79, 57, 37, 21, 10, 2,
   0, 2, 10, 21, 37, 57, 79, 103
};

void setup() {
}

void loop() {
   for (int step = 0; step < 32; step++) {
     analogWrite(outPin, sineLUT[step]);
     delay(3);  // Delay sets frequency
   }
}
```

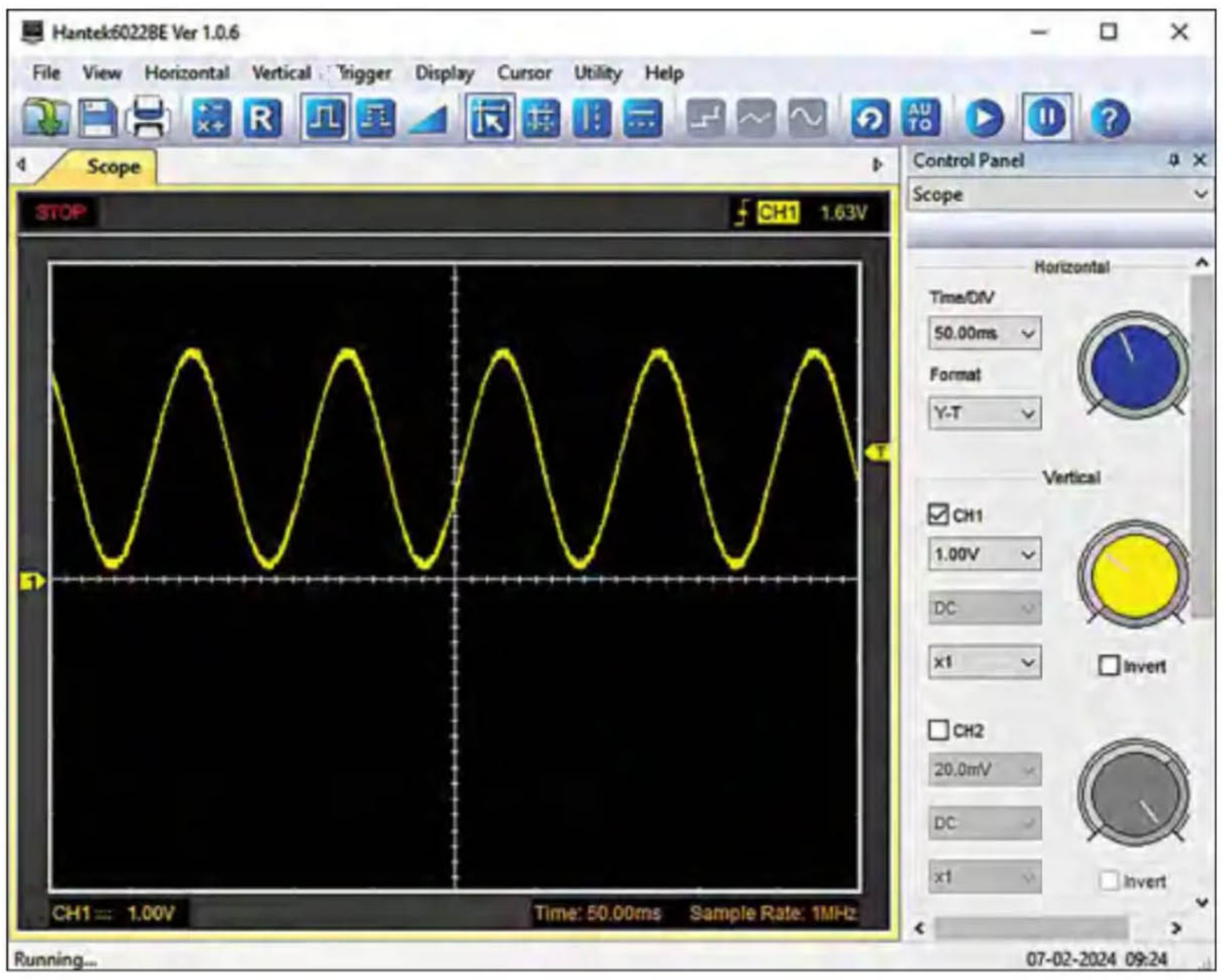

Hantek6022BE Ver 1.0.6
File View Horizontal Vertical Trigger Display Cursor Utility Help
Scope
STOP
CH1 1.63V
Control Panel
Horizontal
Time/DIV
50.00ms
Format
Y-T
Vertical
CH1
1.00V
DC
x1
Invert
CH2
20.0mV
CH1 = 1.00V
Time: 50.00ms
Sample Rate: 1MHz
Running...
07-02-2024 09:24

Fig.3.18. Sinewave output produced by Listing 3.6.

two ways of doing this; first, using a look-up table (LUT) and second, by calculating values using the maths library.

The code in Listing 3.6 produces a sinewave of about $2V_{pk\text{-}pk}$ with a frequency of 10Hz. The output waveform benefits from the addition of the simple C-R low-pass filter (R1 and C1) shown in Fig.3.17. This helps to smooth the output waveform and improve its shape. The frequency can be changed by altering `delay()`. Varying the delay parameter from 1 to 20 will change the frequency from 31Hz to 1.6Hz respectively. Fig.3.18 shows the waveform produced.

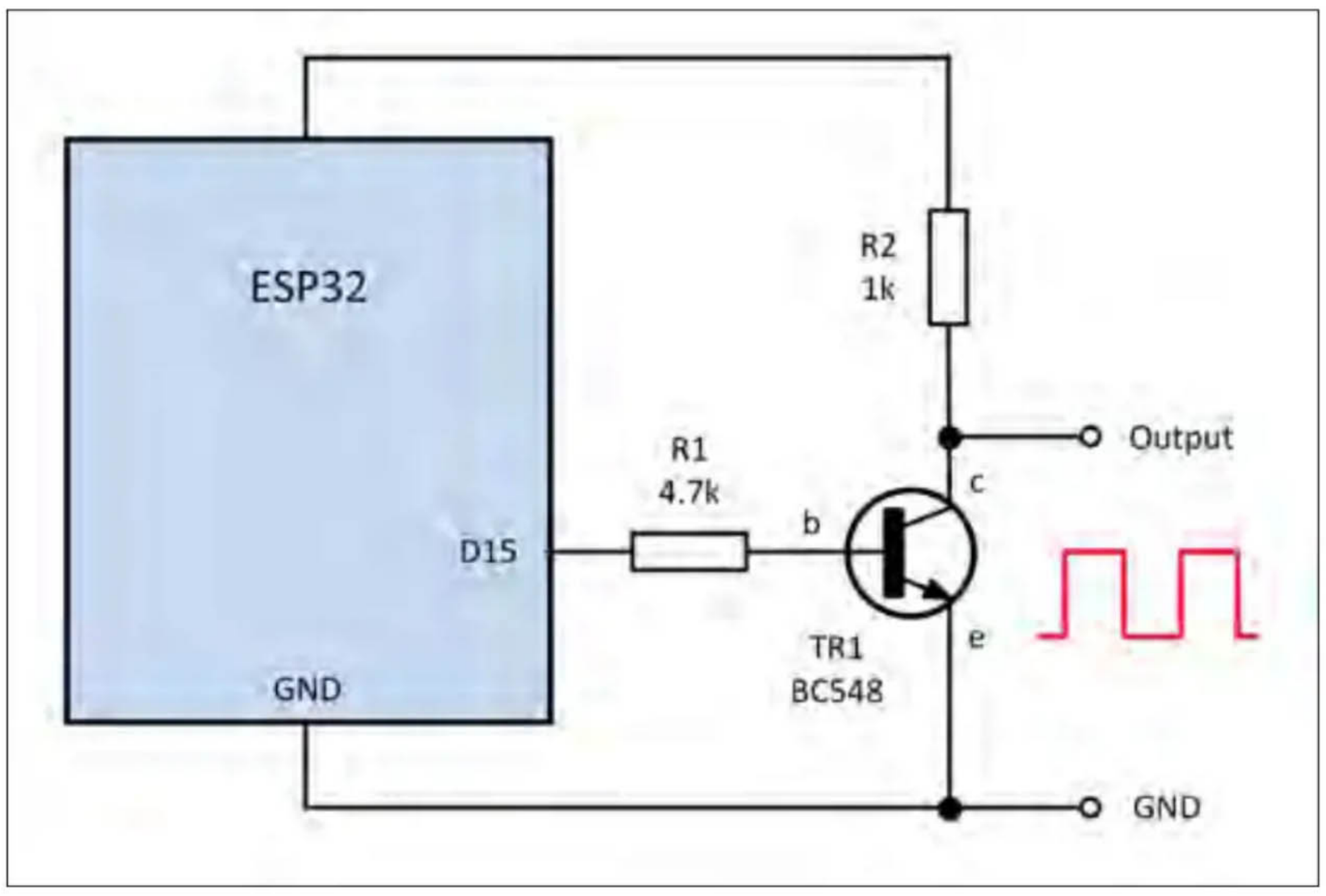

ESP32
D15
GND
R1
4.7k
b
c
e
R2
1k
Output
TR1
BC548
GND

Fig.3.20. Using an external transistor buffer to provide a $5V_{pk\text{-}pk}$ TTL-compatible output.

Listing 3.7 Code for generating a sinewave using maths library

```
/* Low frequency sine wave generator.
This code uses the math library. */

int outPin = 15;  // Use GPIO D15
int level;

void setup() {
}

void loop() {
   for (int step = 0; step < 36; step++) {
     level = 128 + (127 * sin(step * 10 * (6.28 / 360)));
     analogWrite(outPin, level);
     delay(5);  // Delay sets frequency
   }
}
```

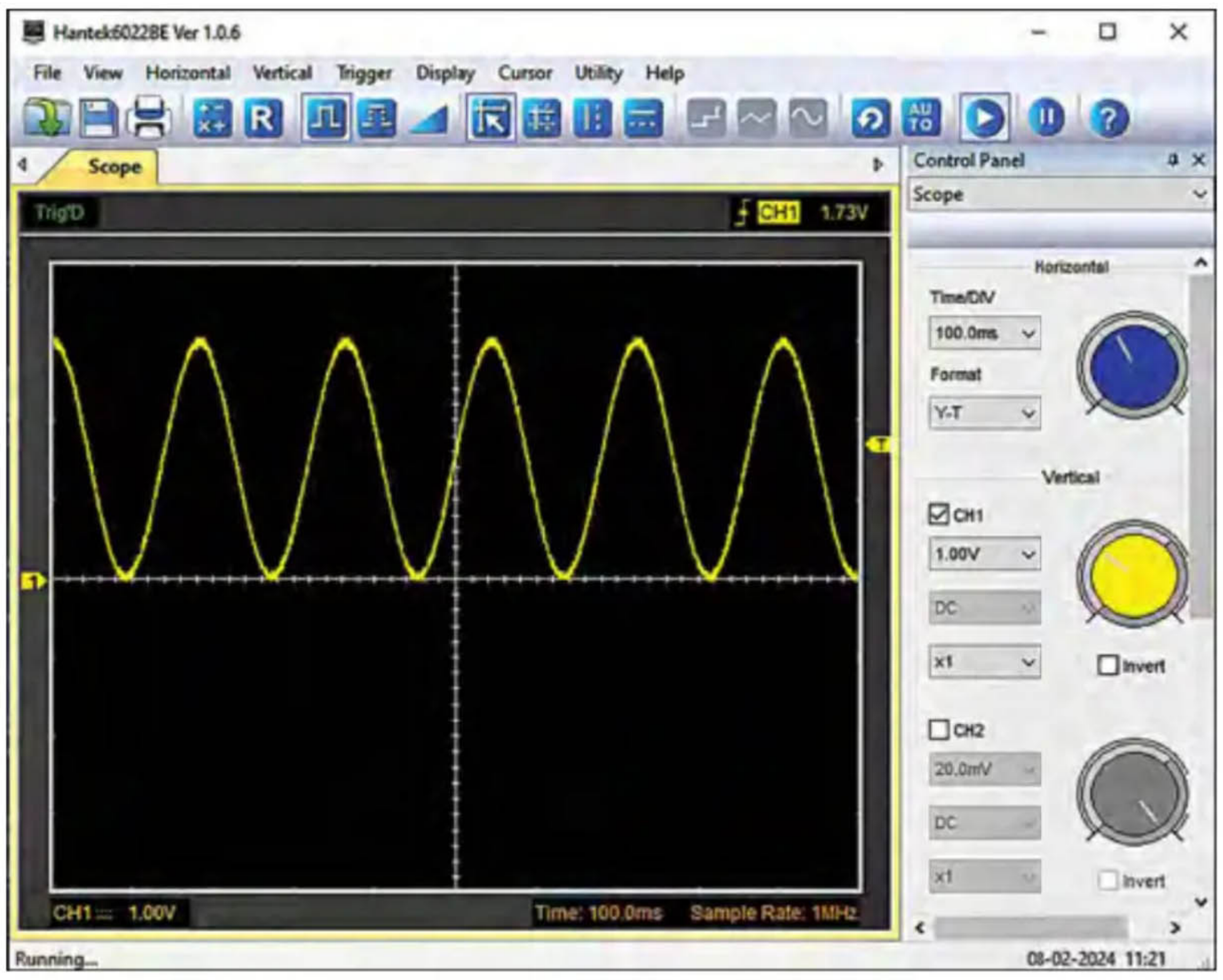

Hantek6022BE Ver 1.0.6
File View Horizontal Vertical Trigger Display Cursor Utility Help
Scope
Trig'D
CH1 1.73V
Control Panel
Horizontal
Time/DIV
100.0ms
Format
Y-T
Vertical
CH1
1.00V
DC
x1
Invert
CH2
20.0mV
CH1 = 1.00V
Time: 100.0ms
Sample Rate: 1MHz
Running...
08-02-2024 11:21

Fig.3.19. Sinewave output produced by Listing 3.7.

Gotcha!

When using the `noTone()` function to turn off your tone you must ensure that the 'T' is in upper case, `notone()` just won't work!

There's another way of generating a sinewave that uses the built-in maths library. Here we repeatedly calculate values as we need them rather than extract them from a look-up table. Listing 3.7 shows how this is done. Once again, the delay parameter sets the frequency of the sinewave output. Fig.3.19 shows the waveform produced.

Using `tone()` and `noTone()`

The ESP32 can generate a simple square wave using the `tone()` function. This is simple and expedient in many applications. For example, the code in Listing 3.8 generates an alarm signal consisting of repeated one-second bursts of 1kHz tone. All that you need is an audible transducer connected between pin-15 and ground.

Generating TTL levels

You may sometimes find that you need to generate a good-quality square wave at TTL (5V logic) levels. This can be easily done by adding an external transistor buffer stage, as shown in Fig.3.20. The TTL-compatible square wave generated by Listing 3.9 is shown in Fig.3.21.

LED brightness control

Another important application of PWM is controlling the brightness of an LED display. This can be easily done by varying the duty cycle of the pulses supplied to an LED,

Listing 3.8 Testing `tone()` and `noTone()` functions

```
/* Tone test */

int outPin = 15;  // Use GPIO D15

void setup() {
}

void loop() {
   tone(outPin, 1000);
   delay(1000);
   noTone(1000);
   delay(1000);
}
```

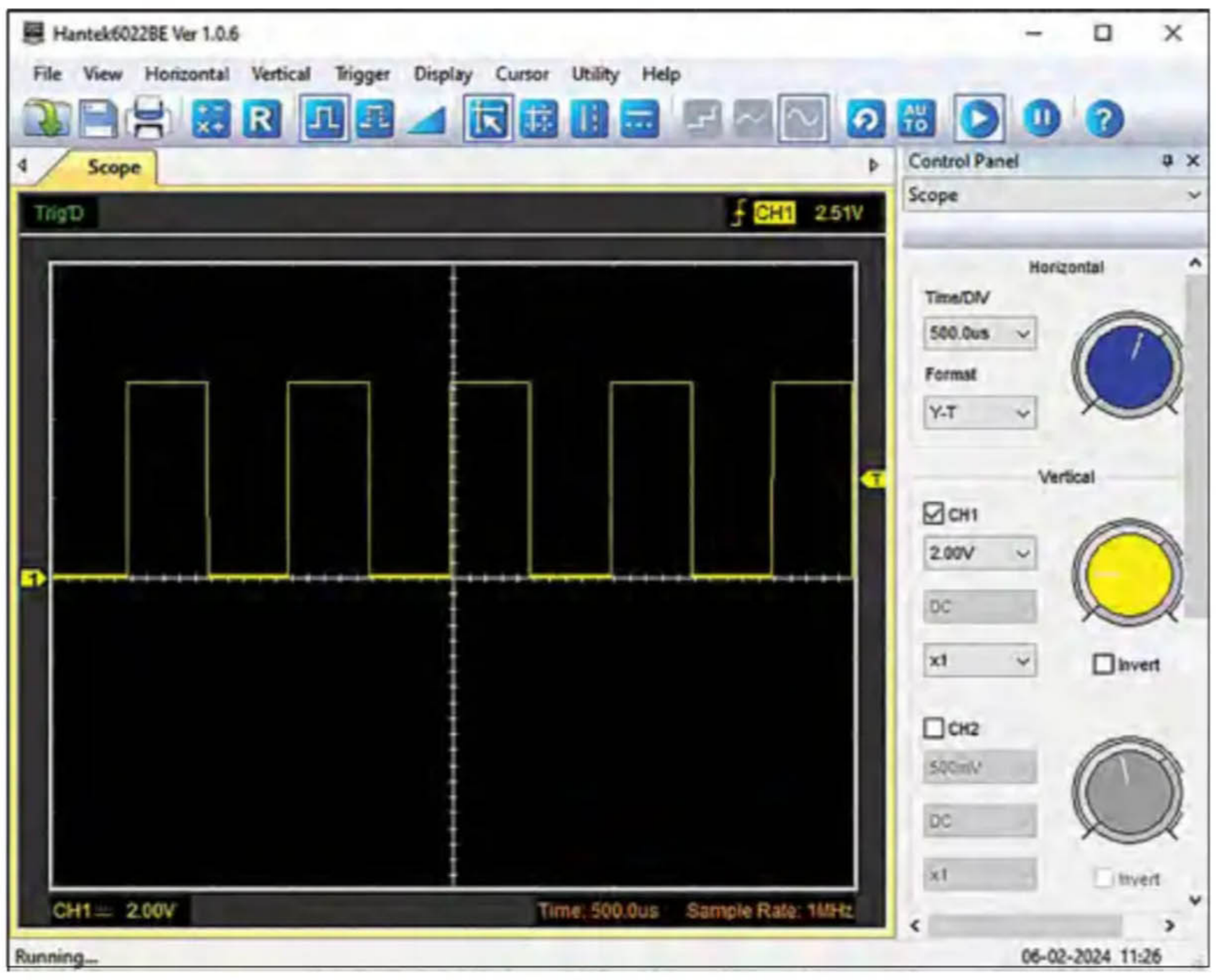


Fig.3.21. A TTL-compatible square wave generated by Listing 3.8 using the transistor buffer shown in Fig.3.20.

Dec.	Binary	Octal	Hex.
0	0000	0	0
1	0001	1	1
2	0010	2	2
3	0011	3	3
4	0100	4	4
5	0101	5	5
6	0110	6	6
7	0111	7	7
8	1000	10	8
9	1001	11	9
10	1010	12	A
11	1011	13	B
12	1100	14	C
13	1101	15	D
14	1110	16	E
15	1111	17	F

Fig.3.22. Denary, binary, octal and hexadecimal numbers.

and the ESP32 provides several functions for doing this, including `ledcSetup()`, `ledcAttachPin()`, and `ledcWrite()`. Listing 3.9 shows how this is done.

Coding Workshop

In this month's *Coding Workshop* we introduce ways of representing numbers and characters in our code. This can be particularly useful when we need to send or receive data to/from external devices. We will start with the base 10 (denary or decimal) number system that we're all familiar with and move on to binary (base 2), octal (base 8) and hexadecimal (base 16) number systems.

Denary (base 10) number system

The denary (or decimal) system of numbers is something that we are all familiar with because we use it every day of our lives. The valid digits in a decimal number are 0 to 9 and the weight of each digit is 10-times greater than the digit immediately to its right. The rightmost digit of a denary integer (ie, a whole number with no fractional part) is the units place, the digit to its left is the tens digit, the next is the 100s digit, and so on. For example, the value of the digits present in the denary number 123 can be accumulated from the following:

$$123_{10} = (1 \times 100) + (2 \times 10) + (3 \times 1)$$

Note that we have used the suffix subscript 10 to indicate the number base. This can help avoid confusion, particularly when different number bases are being used concurrently.

Binary (base 2) number system

In the binary system (base 2), the weight of each digit is *twice* as great as the digit immediately to its right. The rightmost digit of the binary integer is the ones digit, the next digit to the left is the twos digit, next is the fours digit, then the eighths digit, and so on. The only valid digits in the binary system are 0 and 1. For example, the value of the digits present in the binary number 1011 can be accumulated from the following:

$$1011_2 = (1 \times 8) + (0 \times 4) + (1 \times 2) + (1 \times 1) = 8 + 2 + 1 = 11_{10}.$$

Octal (base 8) number system

In the octal (base 8) number system, the weight of each digit is eight times as great as the digit immediately to its right. The rightmost digit of an octal integer is the ones digit, the next digit to the left is the eighths digit, next is the 64s digit, and so on. The valid digits are 0 to 7. For example, the value of the digits present in the octal number 127 can be calculated from:

$$127_8 = (1 \times 64) + (2 \times 8) + (7 \times 1) = 64 + 16 + 7 = 87_{10}$$

Hexadecimal (base 16) number system

Although microcontrollers are quite comfortable working with binary numbers of 8, 16, or even 32 binary digits, humans find it inconvenient to work with so many digits at a time. The hexadecimal (base 16) numbering system offers a practical compromise. One hexadecimal digit can exactly represent four binary digits so an 8-bit binary number can be expressed using just two hexadecimal digits. Hexadecimal notation is thus much more compact than binary notation and often easier to work with than decimal notation.

In the hexadecimal (base 16) number system, the weight of each digit is sixteen times as great as the digit immediately to its right. The rightmost digit of a hexadecimal integer is the ones digit, the next digit to the left is the sixteens digit, next is the 256 digit and so on. The valid digits are 0 to F. Note that, because we have run out of numerical characters beyond 9, we introduce the letters A to F to represent numbers from 10 to 15. Fig.3.22 shows the equivalence between the first sixteen decimal, binary, and hexadecimal numbers.

As an example of hexadecimal notation, the value of the digits present in the hexadecimal number 7F can be accumulated from the following weightings: $7F_{16} = (7 \times 16) + (15 \times 1) = 112 + 15 = 127_{10}$.

Conversion from binary to hexadecimal (and vice versa) is very easily performed by simply arranging the binary number into groups of four digits from right to

Listing 3.9 Using PWM to control LED brightness

```
/* Simple PWM application to slowly increase the brightness
of an LED indicator */

int ledPin = 15;      // Use GPIO D15
int ledChan = 0;      // LED channel
int freq = 1000;      // PWM frequency
int bits = 8;         // 8-bit resolution
int delayTime = 50;   // Delay between levels

void setup() {
   ledcSetup(ledChan, freq, bits);  // Configure the PWM
   ledcAttachPin(ledPin, ledChan);  // and attach the LED
   ledcWrite(ledChan, 0);           // Start with LED off
}

void loop() {
   for (int dutyCycle = 0; dutyCycle <= 255; dutyCycle++) {
     ledcWrite(ledChan, dutyCycle);   // Output to the LED
     delay(delayTime);
   }
}
```

Listing 3.10 Decimal, binary, octal, and hexadecimal table

```
/*
Decimal, binary, octal, and hexadecimal table
*/

void setup() {
   //Initialize serial and wait for port to open:
   Serial.begin(9600);
   while (!Serial) {
      ;  // Wait for the serial port
   }
   delay(1000);
   // Print the table heading and
   // use tabs to separate columns
   Serial.println(“”);
   Serial.print(“Dec.”);
   Serial.print(“\t”);
   Serial.print(“Binary”);
   Serial.print(“\t”);
   Serial.print(“Octal”);
   Serial.print(“\t”);
   Serial.print(“Hex.”);
   Serial.print(“\t”);
   Serial.println(“ASCII”);
}

int lineValue = 64;  // Start value
int endValue = 127;  // End value

void loop() {
   delay(200);
   Serial.print(lineValue);
   Serial.print(“\t”);
   Serial.print(lineValue, BIN);
   Serial.print(“\t”);
   Serial.print(lineValue, OCT);
   Serial.print(“\t”);
   Serial.print(lineValue, HEX);
   Serial.print(“\t”);
   Serial.println(char(lineValue));
   if (lineValue == endValue) {
while (true) {
continue;  // Got to the end!
}
}
lineValue++;  // Go round again ...
}
```

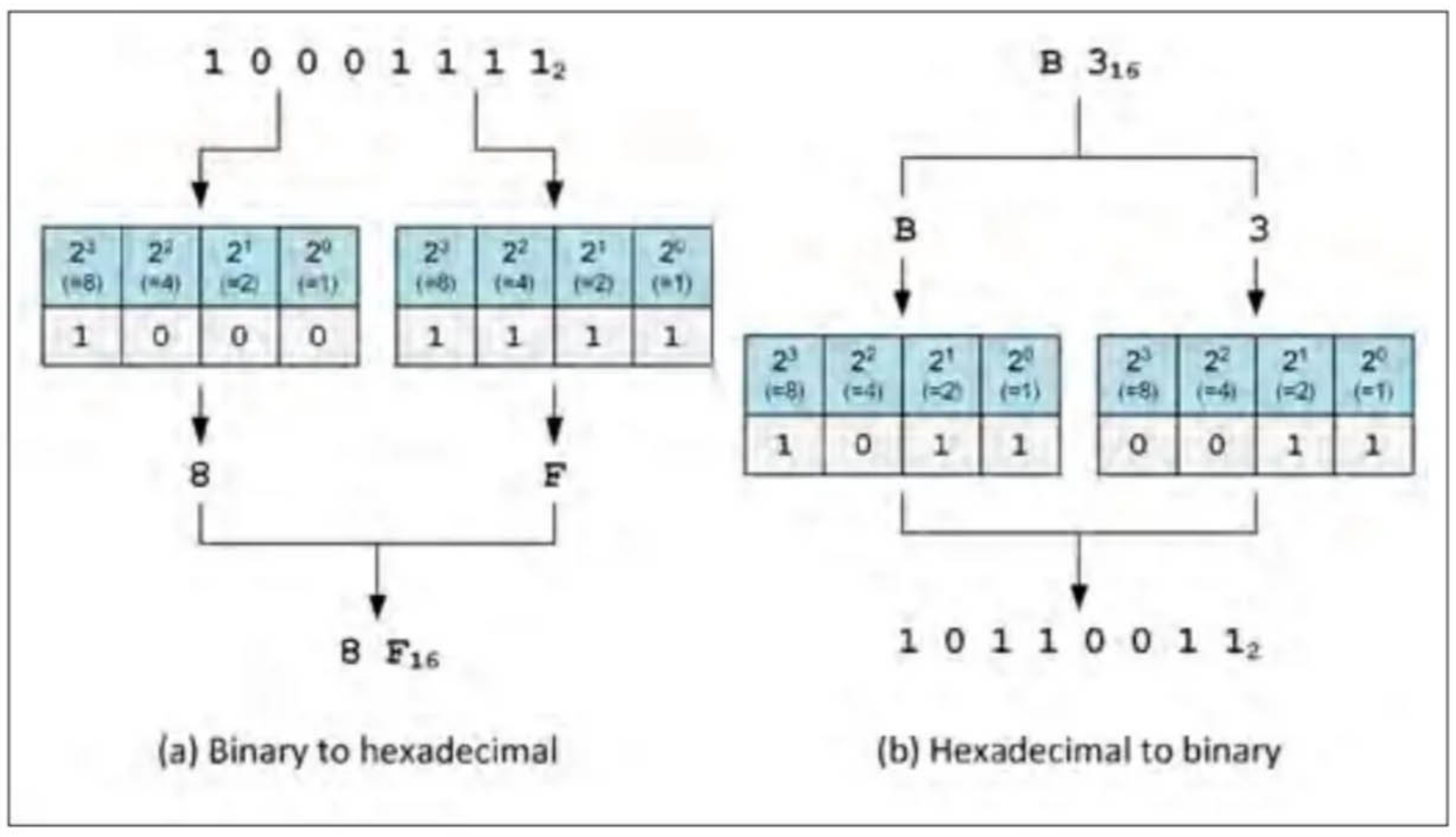
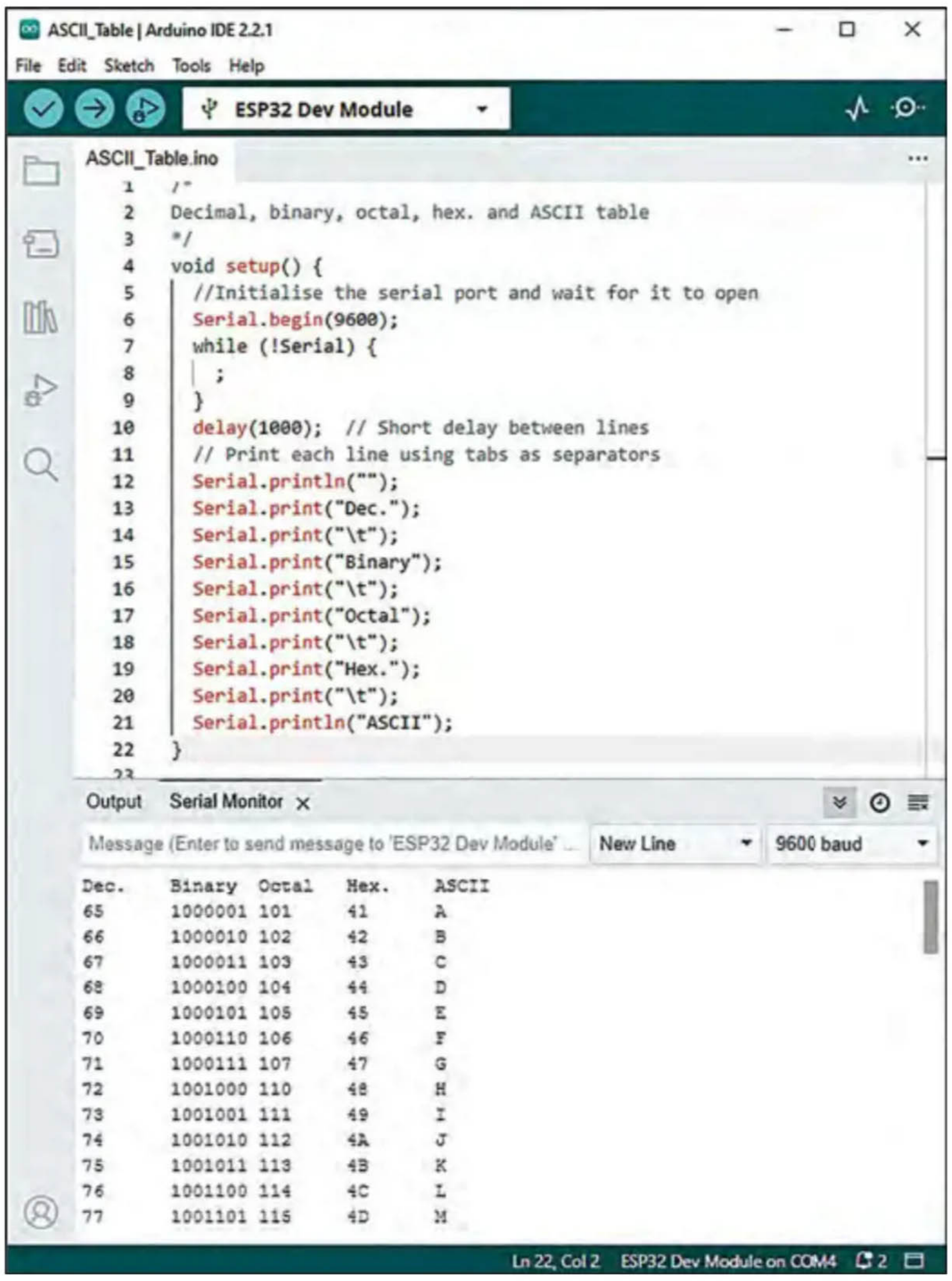

1 0 0 0 1 1 1 1₂
B 3₁₆
2³ (=8)
2² (=4)
2¹ (=2)
2⁰ (=1)
1 0 0 0
1 1 1 1
8
F
B F₁₆
B
3
1 0 1 1
0 0 1 1
1 0 1 1 0 0 1 1₂
(a) Binary to hexadecimal
(b) Hexadecimal to binary

Fig.3.23. Conversion of binary to hexadecimal (and vice versa).


ASCII_Table | Arduino IDE 2.2.1
File
Edit
Sketch
Tools
Help
ESP32 Dev Module
ASCII_Table.ino
Output
Serial Monitor
Message (Enter to send message to 'ESP32 Dev Module' ...
New Line
9600 baud
Ln 22, Col 2
ESP32 Dev Module on COM4
2

```
/*
Decimal, binary, octal, hex. and ASCII table
*/
void setup() {
  //Initialise the serial port and wait for it to open
  Serial.begin(9600);
  while (!Serial) {
    ;
  }
  delay(1000);  // Short delay between lines
  // Print each line using tabs as separators
  Serial.println("");
  Serial.print("Dec.");
  Serial.print("\t");
  Serial.print("Binary");
  Serial.print("\t");
  Serial.print("Octal");
  Serial.print("\t");
  Serial.print("Hex.");
  Serial.print("\t");
  Serial.println("ASCII");
}
```

```
Dec.    Binary  Octal   Hex.    ASCII
65      1000001 101     41      A
66      1000010 102     42      B
67      1000011 103     43      C
68      1000100 104     44      D
69      1000101 105     45      E
70      1000110 106     46      F
71      1000111 107     47      G
72      1001000 110     48      H
73      1001001 111     49      I
74      1001010 112     4A      J
75      1001011 113     4B      K
76      1001100 114     4C      L
77      1001101 115     4D      M
```

Fig.3.24. Serial Monitor display from Listing 3.10.

Table 3.1 Number base prefix

Name	Base	Prefix	Valid digits	Example
Denary	10	none	0 to 9	109
Binary	2	0b	0 and 1	0b11001000
Octal	8	0	0 to 7	0102
Hexadecimal	16	0x	0 to F	0x2C

Gotcha!

It's important to avoid inserting an unnecessary 0 before a number because it will be interpreted as an octal value. So, only use the zero prefix if you really do want to use octal numbers!

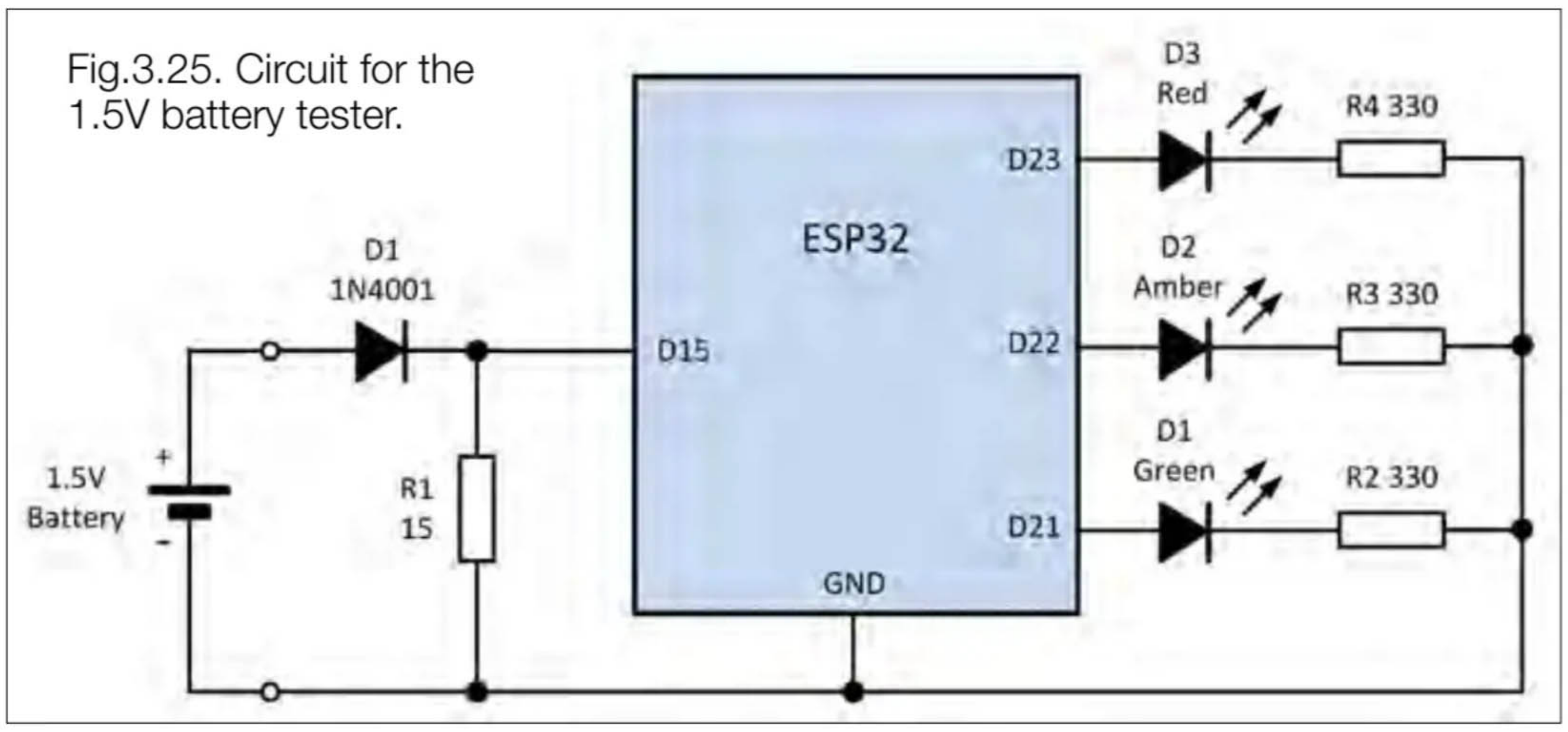
left and then converting each digit to its hexadecimal equivalent, as shown in Fig.3.23.

Number base prefix

When writing code, denary (base 10) is the default way of showing numbers. Binary, octal and hexadecimal numbers are denoted by using a prefix, as shown in Table 3.1.

As an example of using hexadecimal values, the following code fragment show how our sinewave look-up table (LUT) appears when coded in hexadecimal rather than in denary:

Fig.3.25. Circuit for the 1.5V battery tester.


ESP32
D15
D23
D22
D21
GND
D1
1N4001
R1
15
1.5V
Battery
+
-
D3
Red
R4 330
D2
Amber
R3 330
D1
Green
R2 330

```
const uint8_t sineLUT[] = {
0x80,0x98,0xb0,0xc6,0xda,0xea,0xf5,0xfd,
0xff,0xfd,0xf5,0xea,0xda,0xc6,0xb0,0x98,
0x80,0x67,0x4f,0x39,0x25,0x15,0x0a,0x02,
0x00,0x02,0x0a,0x15,0x25,0x39,0x4f,0x67
};
```

When sending data via the Serial Monitor you can have your numerical values printed in decimal (default), binary, octal and hexadecimal. You can also print the corresponding American Standard Code for Information Interchange (ASCII) character. Listing 3.10 shows how this is done. If you enter and execute the code you will be rewarded with a handy reference table like that shown in Fig.3.24. Note, for example, that the ASCII character 'A' can be variously represented by `63` (in decimal), `0b1000001` (in binary), `0101` (in octal), and `0x41` (in hexadecimal).

Practical project

Our *Practical Project* involves the design, construction, and coding of a simple tester for 1.5V alkaline batteries. The tester is to provide three different indications using a 'traffic light' display. A green LED will indicate that a battery is fresh and ready for service. An amber LED will indicate that the battery is partially drained but still serviceable. A red LED will show that the battery is exhausted and should be rejected.

The circuit of the 1.5V battery tester is shown in Fig.3.25. The analogue input of the ESP32 (via D15) is protected by means of silicon diode D1. This component will only conduct when the battery is inserted correctly. If the battery is fitted incorrectly in its holder then the diode will be reverse biased and will not conduct. The 15Ω resistor (R1) provides a test load for the battery which demands a test current of about 50mA (note that 0.7V will be dropped across D1 when it's conducting). The three series current-limiting resistors (R2 to R4) are located on the small 'traffic light' circuit board (see last month for further details). The wiring layout for the 1.5V alkaline battery tester is shown in Fig.3.26.

Listing 3.11 Code for the 1.5V battery tester

```
/* Simple ESP32 1.5V battery tester */

// Assign LEDs to digital I/O lines
int redLED = 23;    // End-of life LED is red
int amberLED = 22;  // Mid-life LED is amber
int greenLED = 21;  // Beginning of life LED is green
int analogPin = 15; // Analogue input via ADC2 Channel 3
float end = 1.1;    // End-of-life threshold = 1.1V
float mid = 1.4;    // Mid-life threshold = 1.4V
float diodeFwd = 0.75;

void setup() {
   // Initialize digital I/O pins outputs
   pinMode(redLED, OUTPUT);
   pinMode(amberLED, OUTPUT);
   pinMode(greenLED, OUTPUT);
   // We need to adjust the thresholds to take into
   // account the forward voltage drop of the diode
   end = end - diodeFwd;
   mid = mid - diodeFwd;
}

void loop() {
   // Get the terminal voltage of the battery on-load
   int rawReading = analogRead(analogPin);
   // Convert the raw reading from the analogue input
   // to volts and store it as floating point
   float volts = rawReading * (3.3 / 4095);
   if (volts > mid) {
// It's above the mid threshold, put green on
digitalWrite(greenLED, HIGH);
digitalWrite(amberLED, LOW);
digitalWrite(redLED, LOW);
   }
   if ((volts > end) && (volts < mid)) {
// It's between the two thresholds, put amber on
digitalWrite(greenLED, LOW);
digitalWrite(amberLED, HIGH);
digitalWrite(redLED, LOW);
   }
   if (volts < end) {
// It'a below the end threshold, put red on
digitalWrite(greenLED, LOW);
digitalWrite(amberLED, LOW);
digitalWrite(redLED, HIGH);
   }
   delay(100);  // Short delay
}
```

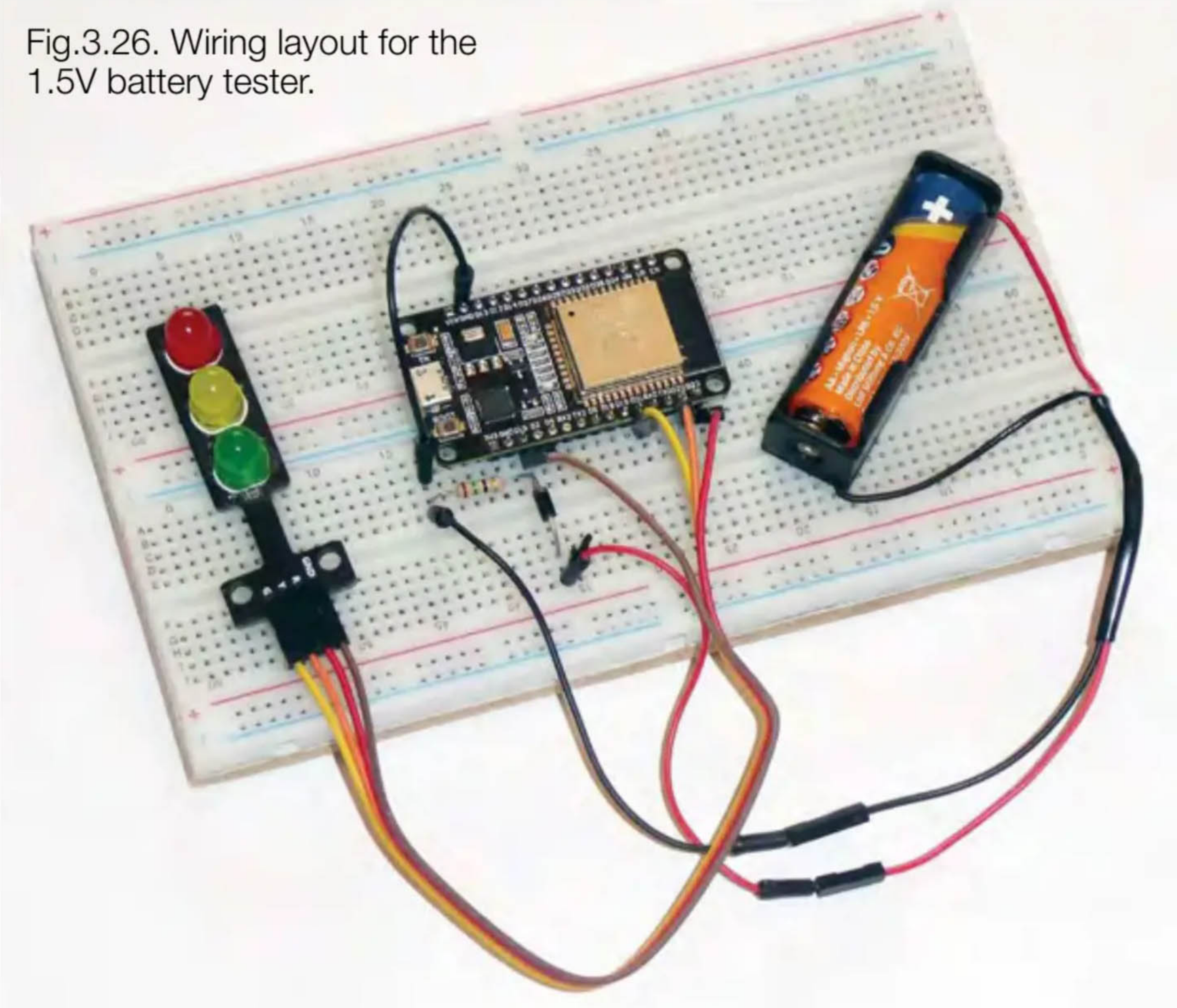


Fig.3.26. Wiring layout for the 1.5V battery tester.

Teach-In Challenge

This month's *Teach-In Challenge* involves a modification to the 1.5V alkaline battery tester. Connect a piezoelectric buzzer between D18 (GPIO18) and ground. Then modify the code so that the tester beeps continuously whenever a fresh battery is inserted into the test holder. This will provide users with an audible indication of the state of a good battery without having to refer to the LED display. Here are the lines that you need to add to the code – but, we will leave you to decide where to add them!

```
int outPin = 18; // Tone ouput for buzzer
tone(outPin, 1000); // Output a beep
delay(500);
noTone(1000);
```

Next month

In *Part 4*, we will introduce seven-segment LED and matrix displays. *Coding workshop* will deal with random number generation and our *Practical Project* will feature a dice roller.

Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 17

A few moments ago, as I pen these words, I was conversing with my son about – let's say an occurrence that had just occurred – when I started to make the comment, 'If there's one good thing to be said for any of this…' and he finished my sentence by saying '…it's not our fault and it's not our problem.' I felt so proud. Despite his habitual look of disinterest when I'm discoursing, it turns out he *has* been listening to me after all.

That's interesting

I'm a digital logic designer by trade. Although we haven't discussed any of this thus far in our bootcamp columns, there are several mathematical tools available to make the lives of digital logic designers simpler, including Boolean algebra, Karnaugh maps, and De Morgan transformations. Don't panic. We aren't going to go into any of these tools here. However, if you do plan on taking a deeper dive into electronics, it would be a good idea to gain some familiarity with these topics. In which case, may I make so bold as to note that they are all introduced in ~~excruciating~~ exhilarating detail in my book, *Bebop to the Boolean Boogie* – see: **https://bit.ly/3u9XIWV**

I often use *Bebop* as a reference myself. The scary thing is that I regularly read something in there and think, 'Wow, that's interesting, I never knew that,' before remembering that I wrote it in the first place. Another book I keep for reference is *Logic Machines and Diagrams* by Martin Gardner (**https://bit.ly/3v7b8DJ**). Martin was one of my heroes. His Mathematical Games columns appeared in *Scientific American* magazine for a quarter of a century.

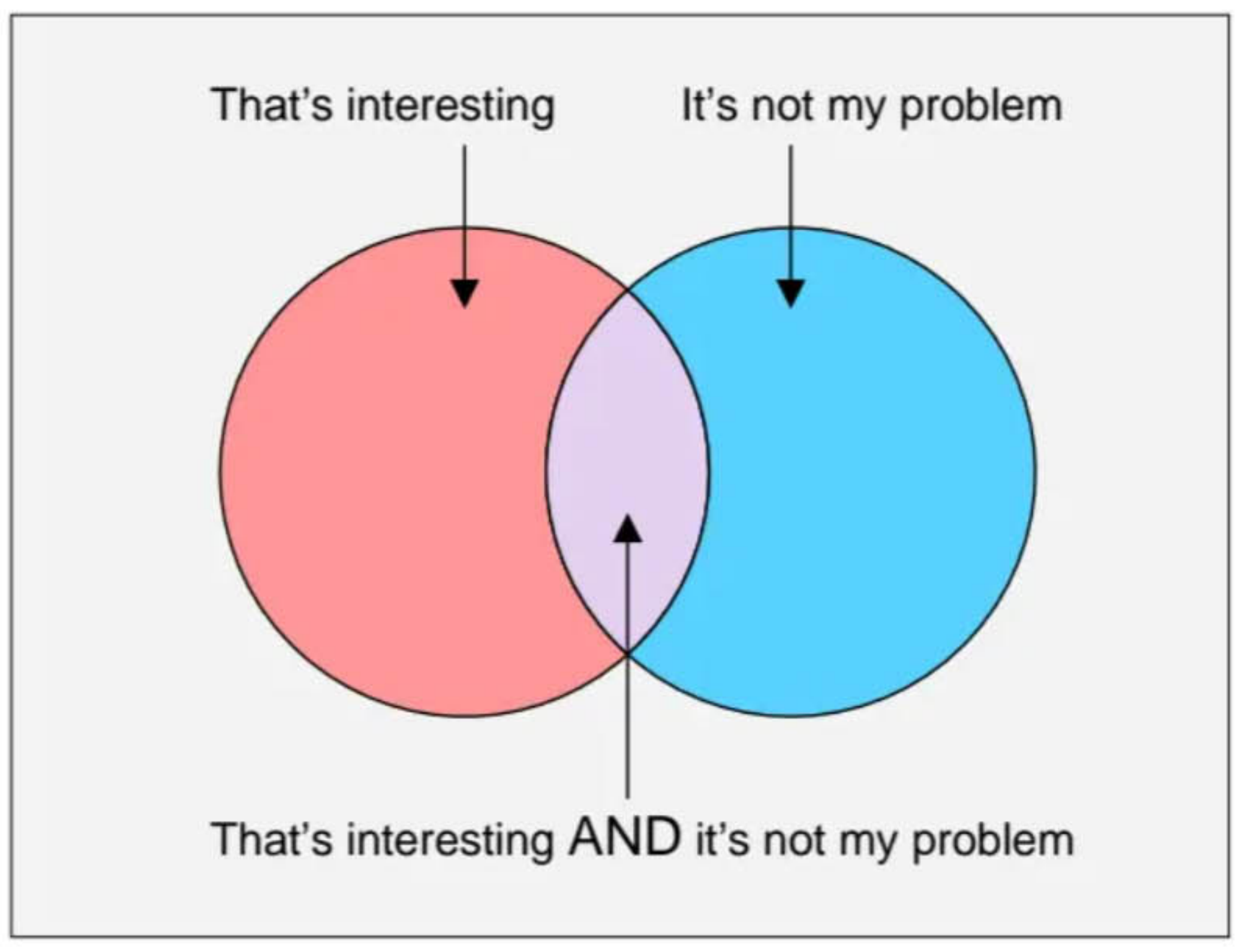


Fig.1. Venn diagram.

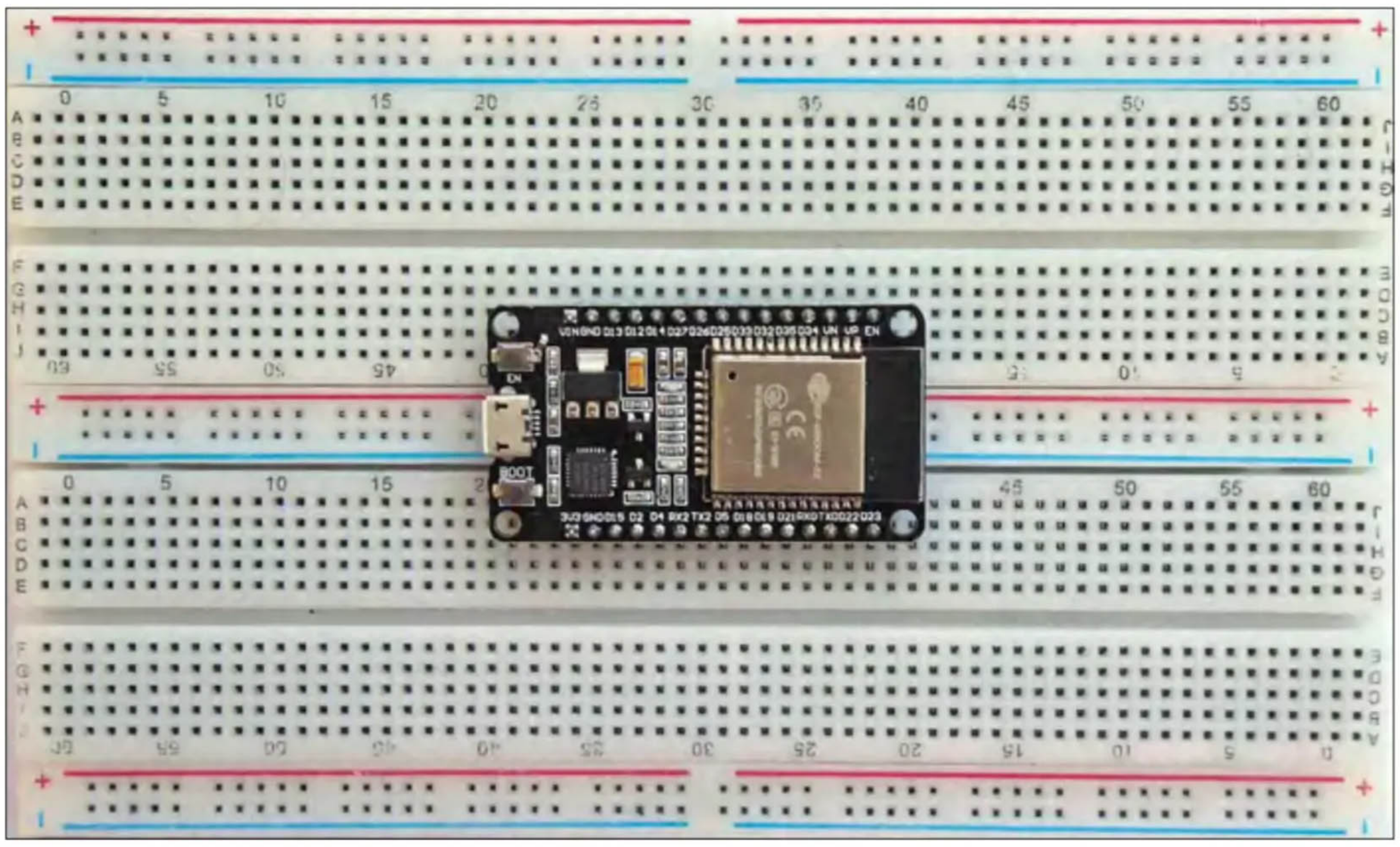


Fig.2. Dual breadboard setup (Source: Mike Tooley / *PE*).

One of the topics covered in Martin's book is Venn diagrams, which typically involve the use of circles to illustrate simple set relationships in areas like probability, logic, statistics and computer science. The reason I mention this here is that I'm bubbling over with glee because I just spotted something that (a) relates to what we've been talking about in recent columns and (b) falls neatly into a Venn diagram intersection of 'that's interesting' and 'it's not my problem' (Fig.1).

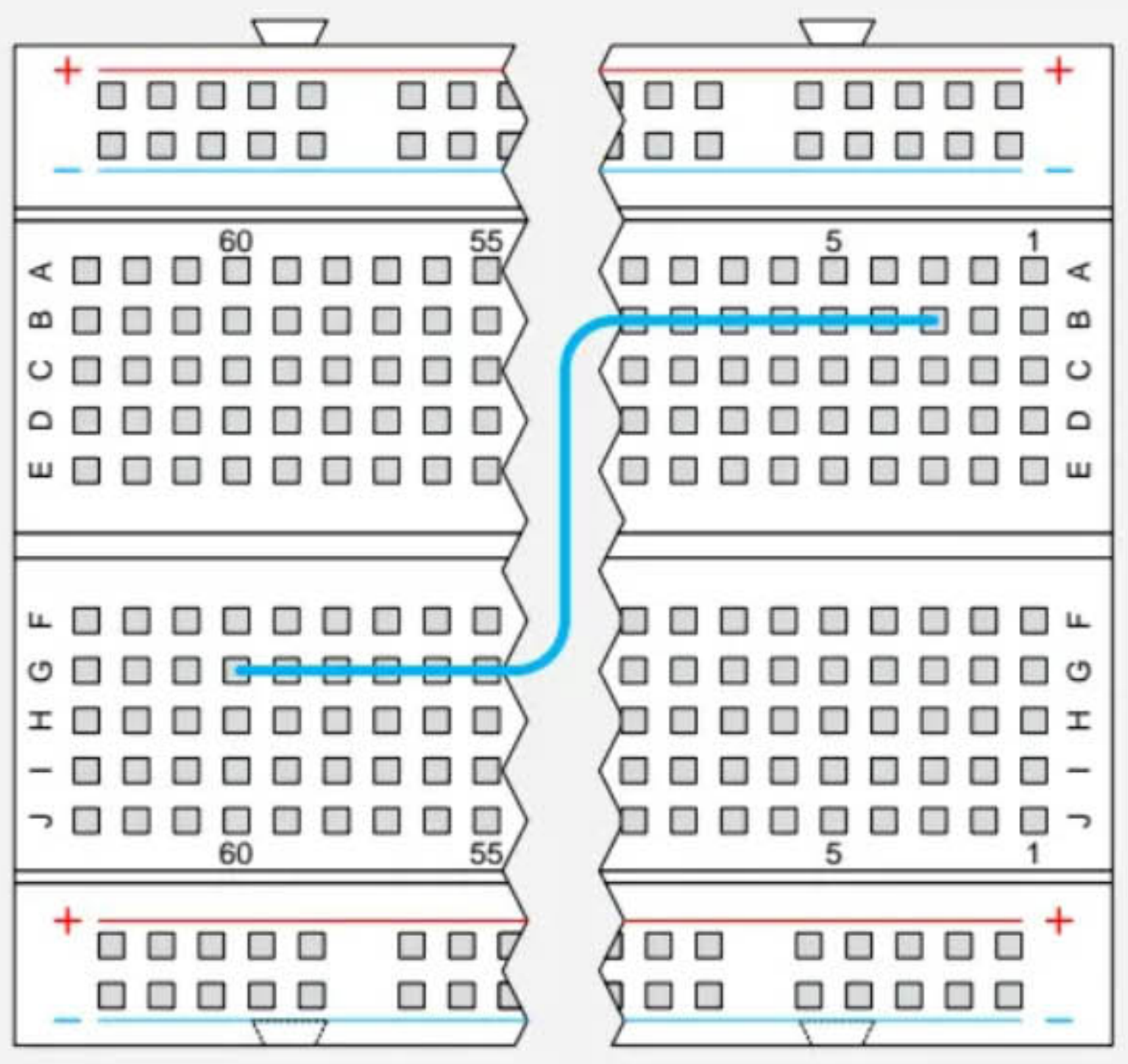
It's not my problem

A couple of columns ago (*PE*, March 2024), we migrated to using a dual-breadboard setup. At that time, we noted that it is possible to remove one or both power and ground rail assemblies from the top and bottom of the breadboard. Did you pause to say to yourself, 'I wonder why anyone would ever want to do such a thing?' Well, as soon as the full March issue of *PE* landed on my desk, I read it cover-to-cover. One item of particular interest to me was *Part 1* of Mike Tooley's *Teach-In 2024 – Learn electronics with the ESP32*. This is going to be awesome. I've never found the time to play with an ESP32, so I'm going to follow this series with great interest.

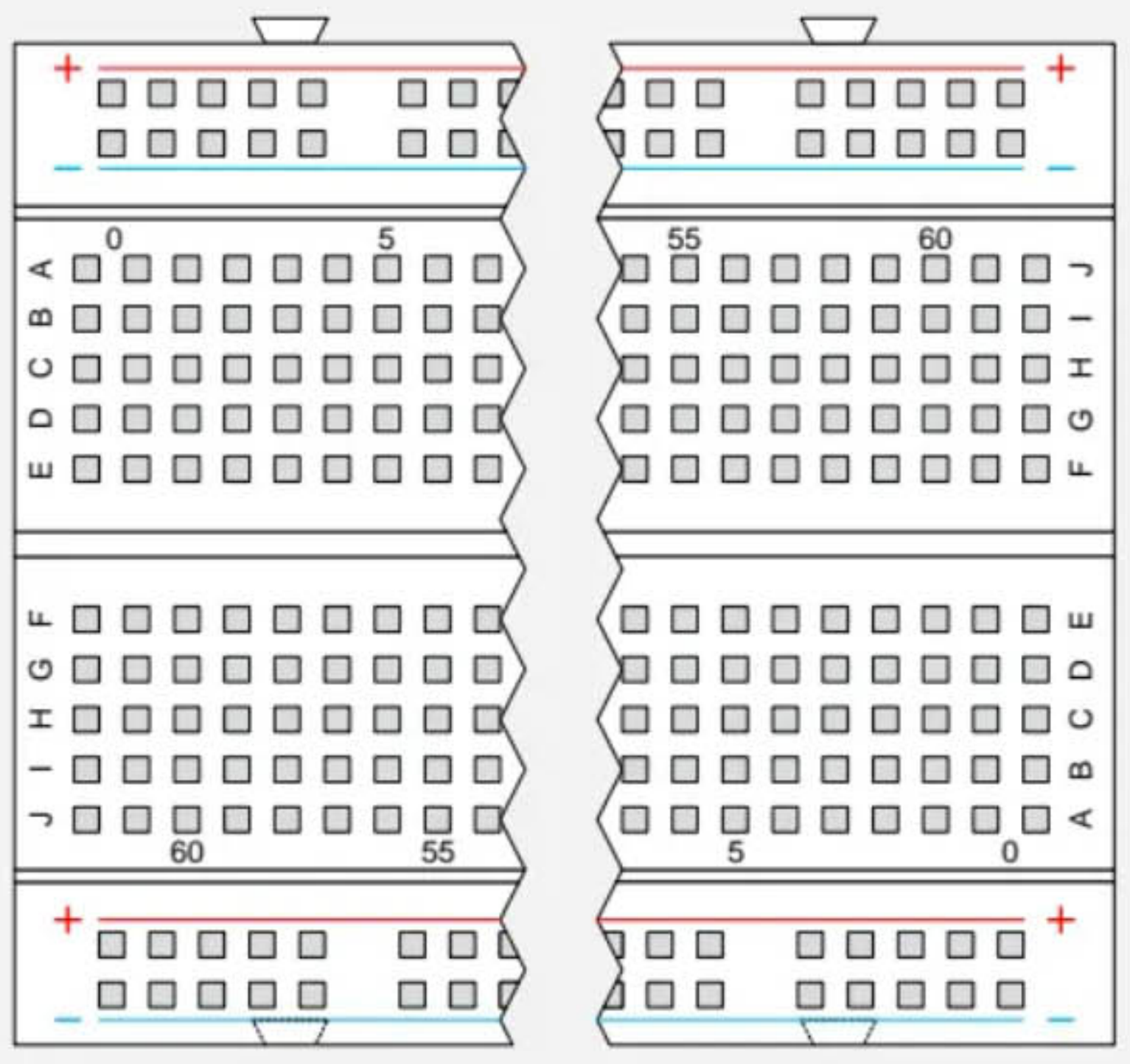
One of the things that immediately caught my eye was the first picture of Mike's breadboard setup, which was accompanied by the caption: 'Two (slightly modified) breadboards provide a convenient space for a 30-pin ESP32 development board.' Look and see for yourself (Fig.2). Do you spot anything interesting and/or unusual? Jot down a list and then we can compare notes.

The first thing I observe is the gaps in the middle of the red and blue horizontal lines reflecting the power and ground rails, respectively. This indicates that the conducting rails inside the breadboard are themselves split. As we discussed in my *Arduinos and Solderless Breadboards* blog (**https://bit.ly/3PdnqBk**), these 'split-rail' boards make it easier to work with circuits that require a mix of power supplies, like 5V and 3.3V, for example. If Mike is intending to use only a single supply, then he will add jumpers to link both sides of the power rails and both sides of the ground rails.

Now look at the middle of Mike's dual-board setup. The ESP32 is so wide that if we tried plugging it into just one board, there would be no free terminal holes on one side and only one free hole next to each of the pins on the other side. As we see, Mike has removed the upper power and ground assembly from the



(a) My breadboards



(b) Mike's breadboards

Fig.3. Can you spot the difference?

lower board before connecting the boards together. This allows his ESP32 to span the two boards while still leaving two free breadboard terminal holes next to each of its pins.

Thus far, everything reflects what we've discussed in our earlier columns. I've saved the best (or worst, depending on your point of view) for last. Suppose you are playing a remote game of chess. If it's your opponent's turn and they send you a message saying 'Qf3,' then you know they've just moved their queen to the square located on file (column) f and row 3. The reason you know this is because everyone who plays chess has adopted a standard notation for describing and recording the moves.

Similarly, there are occasions when it may be advantageous to be able to document instructions for populating a breadboard with components and wires using some form of standard notation along the lines, 'Connect a 150Ω resistor between locations (x1,y1) and (x2,y2)' or 'Connect a wire between locations (x3,y3) and (x4,y4).' But what form of notation should we use to identify our (x,y) values?

Suppose you were the inventor of the original breadboard. One approach might be to use the letters A through E and F through J to identify the rows while also employing numbers to identify the columns. Well, that seems to be simple enough. I mean, seriously, how complicated could it be? More complicated than you might think.

Let's start with the breadboards I've been using (Fig.3a). As we see, the letters A through J are associated with the rows at each end. Assuming we have the red power rail on the top (which is how I prefer to work), then the columns are numbered from 1 on the right to 63 on the left.

Personally, I would have preferred the numbers to start with 1 on the left and increment as we move to the right. Of course, they do this if we rotate the board 180° clockwise (or anticlockwise, for that matter), but then we would have the ground rail on top, which would cause me to wear my frowny face.

Now look at Mike's breadboards (Fig.2 and Fig.3b). In this case, the count starts at 0, which actually makes good sense on several levels. However, for reasons unknown (unless it's to vexeth us greatly), rather than associating the 0 with the leftmost or rightmost column, all the boards I've seen like this have the 0 positioned halfway between the second and third columns, thereby requiring us to count back from column 5 to determine with which column the 0 is related. Also, this leads us to the realisation that the leftmost column is numbered –1. Color me confused.

It gets worse. If you look at row A in the upper left of one of Mike's boards and follow it horizontally to the right, it ends up as row J. Similarly, if you look at column 0 in the upper left of the board and follow it vertically to the bottom, it ends up as column 61.

Other than having rotational symmetry, which benefits us not at all, this annotation scheme has nothing whatsoever to recommend it. For example, if you are using a board as shown in Fig.3a, there is no ambiguity if you are instructed to 'Connect a wire between B3 and G60.' By comparison, following this instruction is more than problematic if your board is as shown in Fig.3b because there are two locations that can be addressed as B3 and two more that can be referenced as G60.

Happily, if there's one good thing to be said for any of this… it's not my fault and it's not my problem!

Preparing to rock and roll

Just to set the scene, let's remind ourselves that we now have two common-cathode 7-segment displays in play. In addition to their ground pins (their common cathodes), each display has eight segment (anode) pins (the decimal point counts as a segment), so 16 anode pins in all.

As we noted in our previous column (*PE*, April 2024), the Arduino Uno has 14 digital I/O pins numbered 0 to 13. We are reserving pins 0 and 1 for UART communications with our host computer, which leaves 12 pins for us to work with.

The problem is that our dual displays require 2 x 8 = 16 pins. This is a bit of a poser. A conundrum, some might say. The solution we decided to adopt (at least, for the moment) is to use eight of the Arduino's pins (pins 2 to 9) to drive both displays in parallel (side-by-side). Also, for each display, we've added a BC377 transistor to control its ground pin. Arduino pins 10 and 11 are used to control displays D0 and D1, respectively (Fig.4).

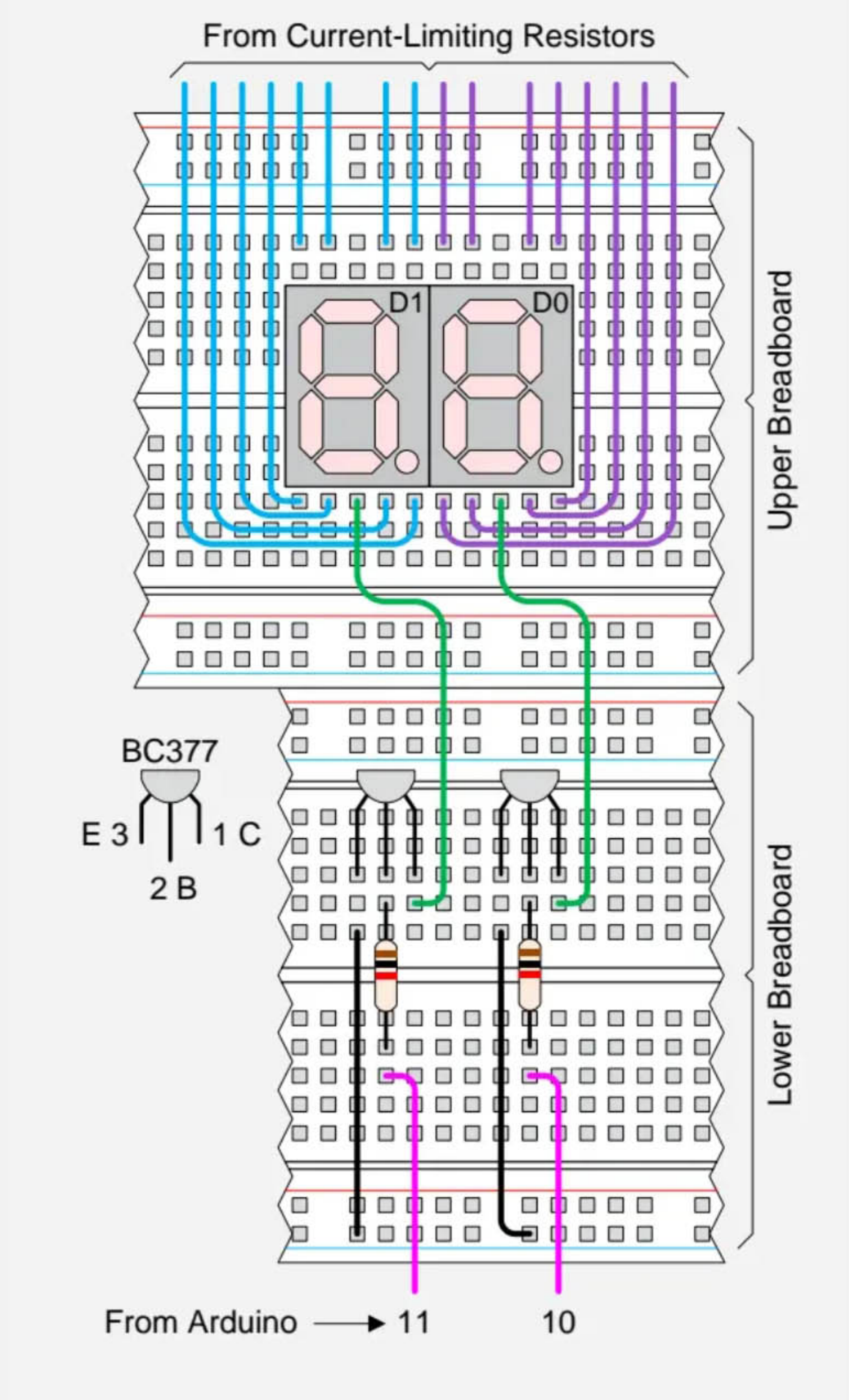


Fig.4. Controlling the displays with transistors.

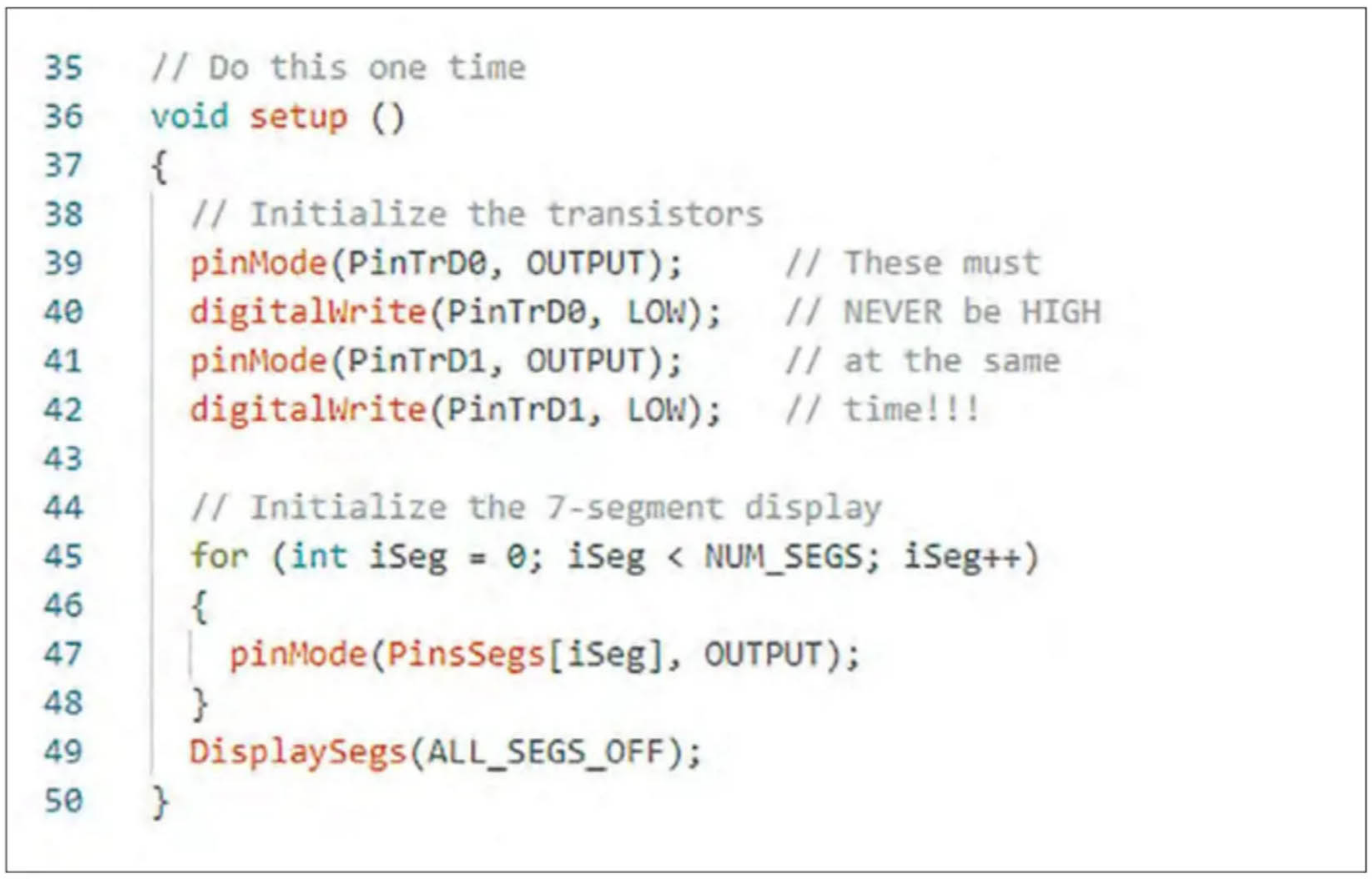
You can remind yourself of our entire current setup by downloading, perusing, and pondering of our latest and greatest incarnation (file **CB-May24-01.pdf**). As usual, all of the files that are mentioned in this month's column are available from the May 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

As one final reminder, our BC377 transistors are of a type known as NPN. The way we are using these transistors in this circuit, we can think of them as acting like switches. In the case of an NPN transistor, applying 0V (LOW) to its control terminal (the base, B) will turn the transistor off, which means it will act like an open switch. In turn, this means the ground pin on the display can't activate any of the light-emitting diode (LED) segments, even if the Arduino is trying to light them up.

By comparison, applying 5V (HIGH) to the transistor's base will turn it on, which means it will act like a closed switch between its collector (C) and emitter (E) terminals. This will effectively connect the display's ground pin to the breadboard's ground (0V) rail, which means any of its segments being powered by the Arduino will light up.

Firing up our two displays

This bit is *very important*. Since our two displays are wired in parallel, we must



```
35  // Do this one time
36  void setup ()
37  {
38    // Initialize the transistors
39    pinMode(PinTrD0, OUTPUT);     // These must
40    digitalWrite(PinTrD0, LOW);   // NEVER be HIGH
41    pinMode(PinTrD1, OUTPUT);     // at the same
42    digitalWrite(PinTrD1, LOW);   // time!!!
43
44    // Initialize the 7-segment display
45    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
46    {
47      pinMode(PinsSegs[iSeg], OUTPUT);
48    }
49    DisplaySegs(ALL_SEGS_OFF);
50  }
```

Listing 2a. The `setup()` function for first test.

ensure that only one of them is active at any time. If both displays are active at the same time, our Arduino will be very unhappy. In a crunchy nutshell, this means we must *never* drive the Arduino's 10 and 11 pins HIGH at the same time.

As I've noted on many previous occasions, it's almost invariably a good idea to take things one step at a time, verifying that any new additions to our system work in isolation before bringing everything together. It's a lot easier to debug things when there are only a limited number of things that can go wrong (as I just found to my cost).

Let's start by creating a little program that commences with both our D1 and D0 displays being turned off. The program will then repeatedly count from 0 to 9, first presenting the value on D1 for one second, then turning D1 off and presenting the same value on D0 for one second, then turning D0 off and proceeding to the next value.

Take a few moments to think about how we might implement this. Maybe you could create your own test program and then compare your approach to my solution (file **CB-May24-02.txt**).

As usual, we won't go through the entire program line-by-line here. Instead, we will focus only on the interesting bits. Note that, from our earlier programs, `NUM_SEGS` ('number of segments') and `NUM_DIGITS` ('number of digits') are defined as 8 and 10, respectively. Also, `ON_OFF_TIME` is defined as 1000 (one thousand milliseconds, or one second). Last, but not least, `PinTrD0` and `PinTrD1` are integer variables that we've associated with the Arduino pins we're using to drive our two transistors.

Lert's start with the `setup()` function as seen in Listing 2a. The first thing we do on Lines 39 through 42 is tell the Arduino that the two pins driving our transistors are of type `OUTPUT` and set them driving `LOW` values. Next, on lines 45 through 48 we tell our Arduino that the pins we are using to drive the segments in our displays are of type `OUTPUT`. Finally, on Line 49 we call our trusty old `DisplaySegs()` function to turn all the segments off.

To be honest, line 49 is superfluous to requirements because we already know that the transistors controlling the displays are turned off, but it never hurts to make sure.

The interesting part of this program takes place in the `loop()` function, as seen in Listing 2b. We start on Line 56 with a `for()` loop that counts from 0 to 9. On line 58 we use our `DisplaySegs()` function to apply power to the segments associated with the current digit on both displays.

The important thing to note here is that, even though we are applying power to the segments, nothing will light up because the transistors associated with both displays are currently off.

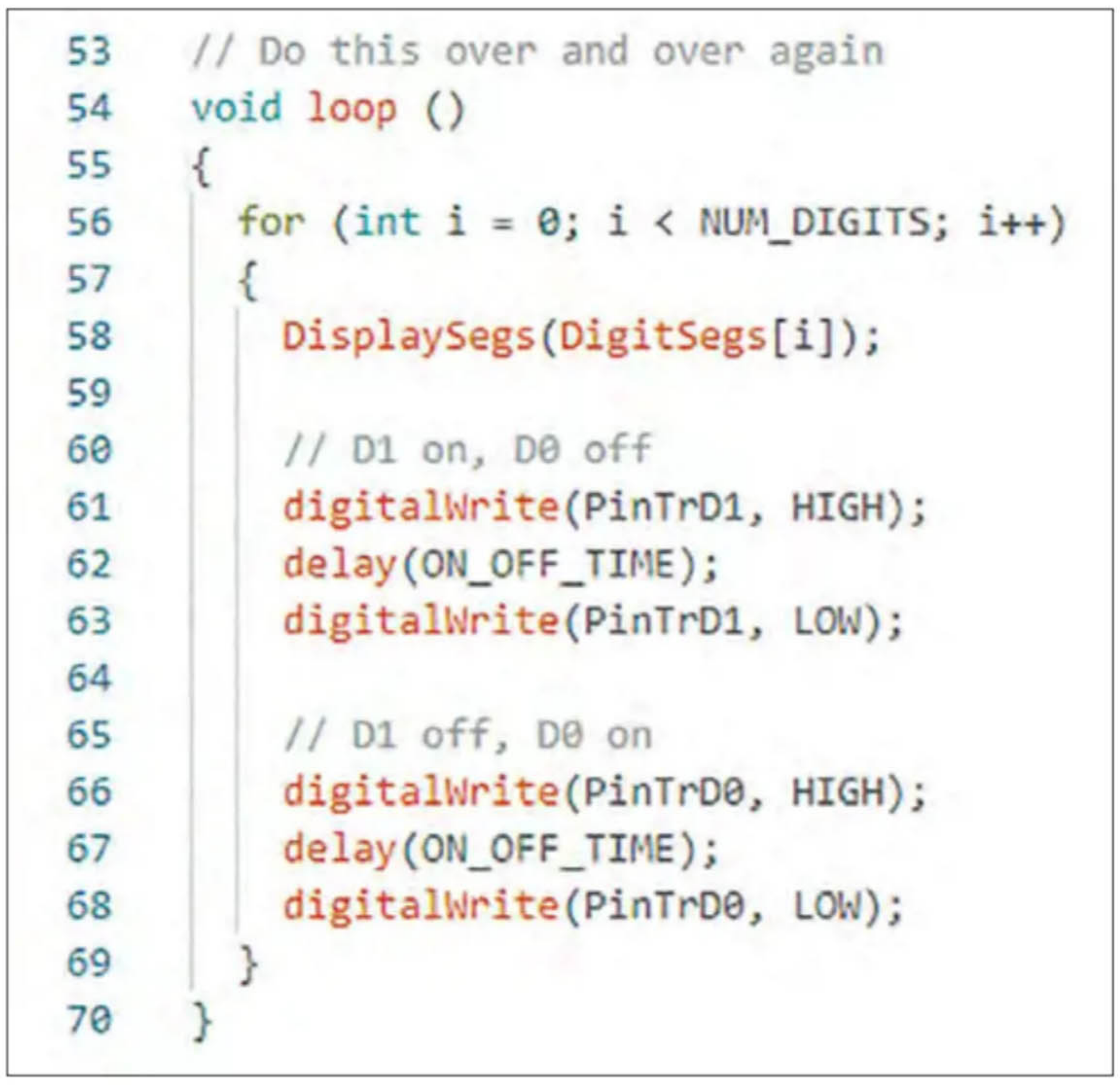
On Lines 61 through 63, we turn display D1 on, wait one second, and turn it off again. On Lines 66 through 68, we turn display D0 on, wait one second, and turn it off again. Then we move onto the next count in our `for()` loop and do it all again. Once we've displayed all the digits 0 through 9, the `for()` loop terminates, at which point we proceed to the next iteration of the main `loop()` function.

So, there you have it. Easy peasy lemon squeezy. What could possibly go wrong? I'm so glad you asked…

Arrrggghh

When I set my program running, it appeared to be functioning 98% (give or take) as planned. How did I come up with this particular percentage? Well, as Homer Simpson famously said, 'People can come up with statistics to prove anything; 40% of all people know that.'

The bottom line is that everything worked as expected except… whenever



```
53  // Do this over and over again
54  void loop ()
55  {
56    for (int i = 0; i < NUM_DIGITS; i++)
57    {
58      DisplaySegs(DigitSegs[i]);
59
60      // D1 on, D0 off
61      digitalWrite(PinTrD1, HIGH);
62      delay(ON_OFF_TIME);
63      digitalWrite(PinTrD1, LOW);
64
65      // D1 off, D0 on
66      digitalWrite(PinTrD0, HIGH);
67      delay(ON_OFF_TIME);
68      digitalWrite(PinTrD0, LOW);
69    }
70  }
```

Listing 2b. The `loop()` function for first test.

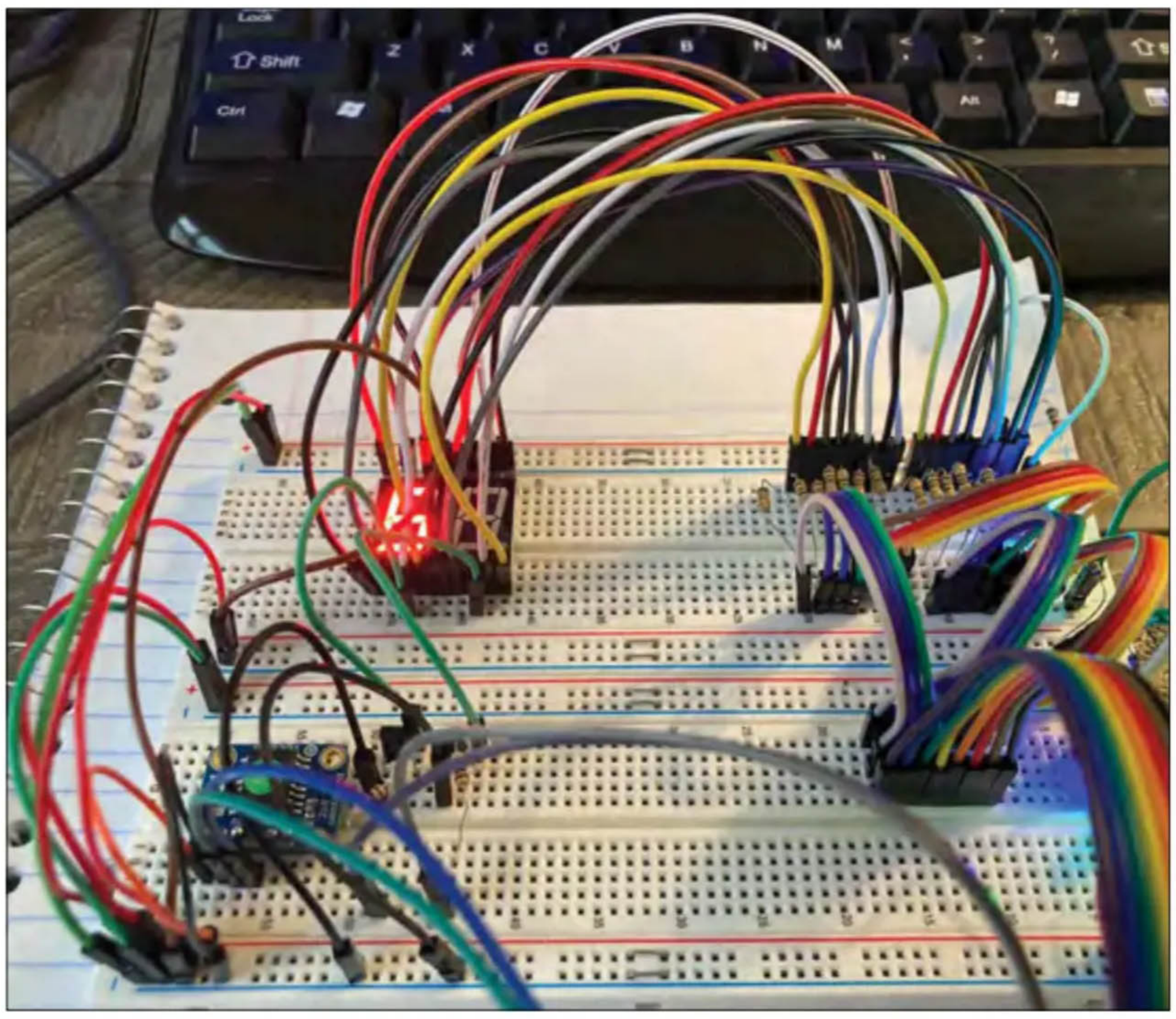


Fig.5. Welcome to the real world (we hope you'll enjoy your stay).

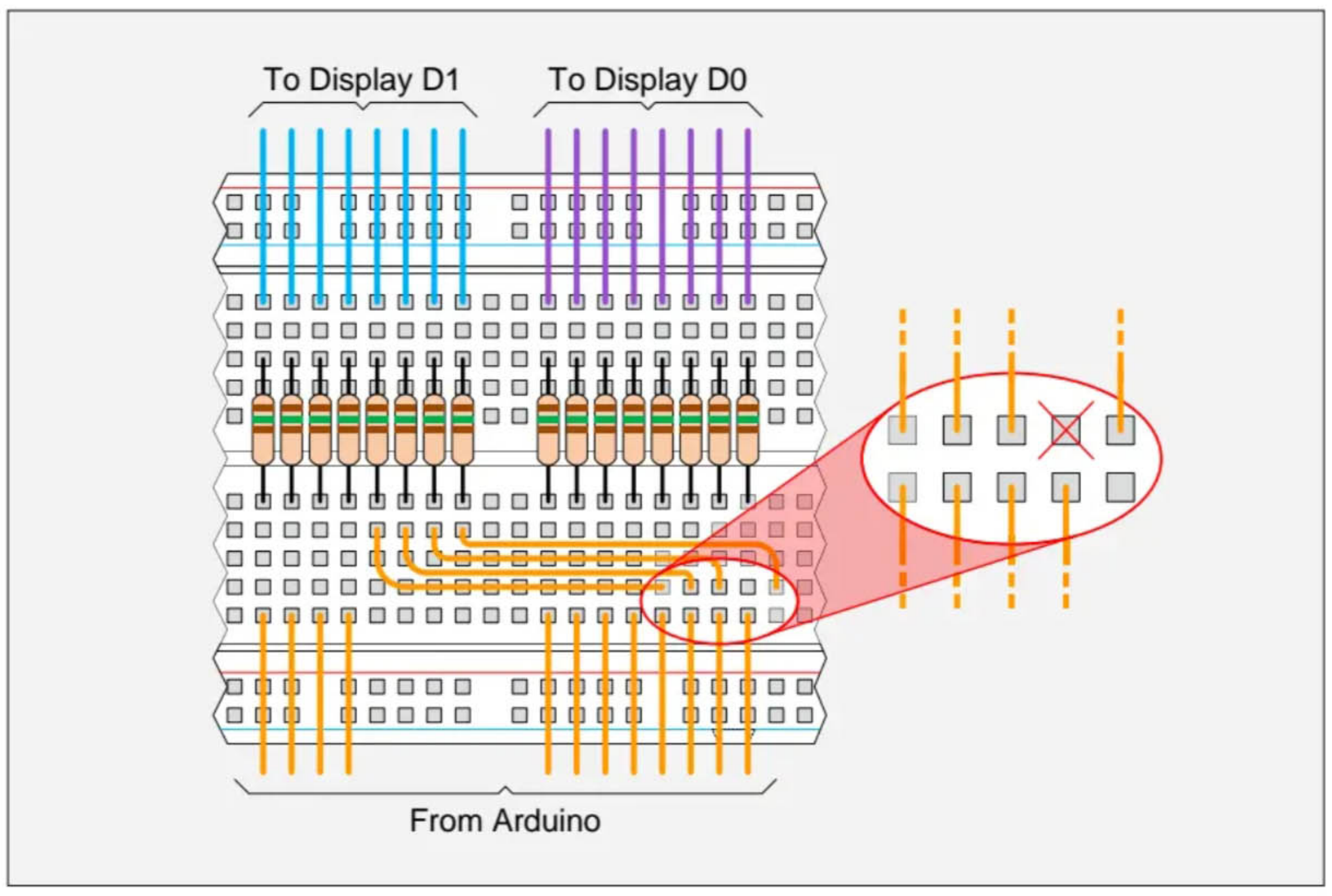


Fig.6. Ah! There's the little scamp!

display D1 was activated, segment A was on for every digit. Even more puzzling, it was noticeably dimmer than any of the other segments on either display. 'Oh dear,' I said to myself (or words to that effect).

Why am I telling you about this? Well, it's not uncommon for things to fail to function as planned, so you'll probably run into something like this yourself at some stage in your experiments. Hopefully, my problem, and the investigation thereof, will provide a 'teachable moment,' as they say. You're welcome.

The first thing I did was to swap the two 7-segment displays. The problem remained with segment A on the new D1 display.

Next, I unplugged the end of the blue wire driving pin 7 (segment A) of D1, I unplugged the end of the purple wire driving pin 7 (segment A) of D0, and I connected them into the other's display (any references to the colours of wires relate to my illustration in file **CB-May24-01.pdf**). Now, the always-on, low-intensity segment A appeared on D0. 'Hmm,' I thought to myself.

I tried swapping out the jumper wire driving the errant segment. No change. Next, I swapped out the resistor driving the wire connected to the misbehaving segment (plus I used my multimeter to confirm that the original resistor's value was as it should be). No change.

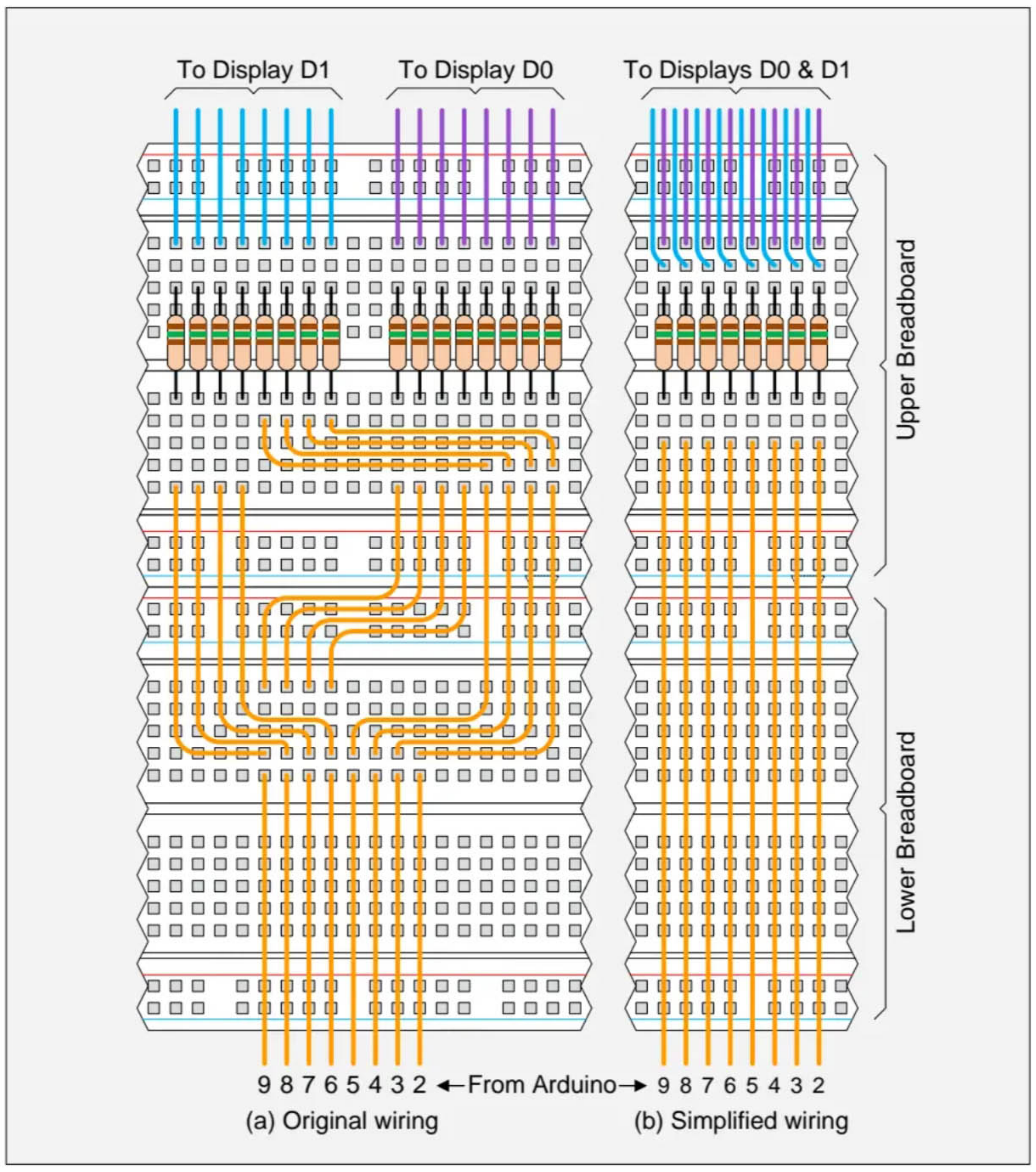


Fig.7. One set of current-limiting resistors will suffice.

I also checked that none of my resistor leads were touching each other, and I rechecked all my connections and wiring. Everything *appeared* to be OK. Eventually I did what I always do in these circumstances – I set up a Zoom call with my chum, Joe Farr, in the UK, and we talked our way through things.

It wasn't long until we decided that there just had to be a problem with my wiring or – possibly – the internals of the breadboard. The thing is that the real world (see Fig.5) looks very different to my artistic interpretation (file **CB-May24-01.pdf**).

So, I went through everything step-by-step one more time. Do you recall when I said that my wiring *appeared* to be correct? It turned out I hadn't looked closely enough. I'd plugged one of my flying leads one hole to the right (Fig.6). Everything looked great when viewed from every angle, *except* the angle I hadn't viewed things from. Give me strength!

As soon as I repositioned the errant wire, everything started to function as expected. I was a happy chappy. The radiance of my smile once more lightened the world. I was basking in the belief that I hadn't made any more mistakes when… Joe inquired why I had decided to use two sets of current-limiting resistors.

Good grief!

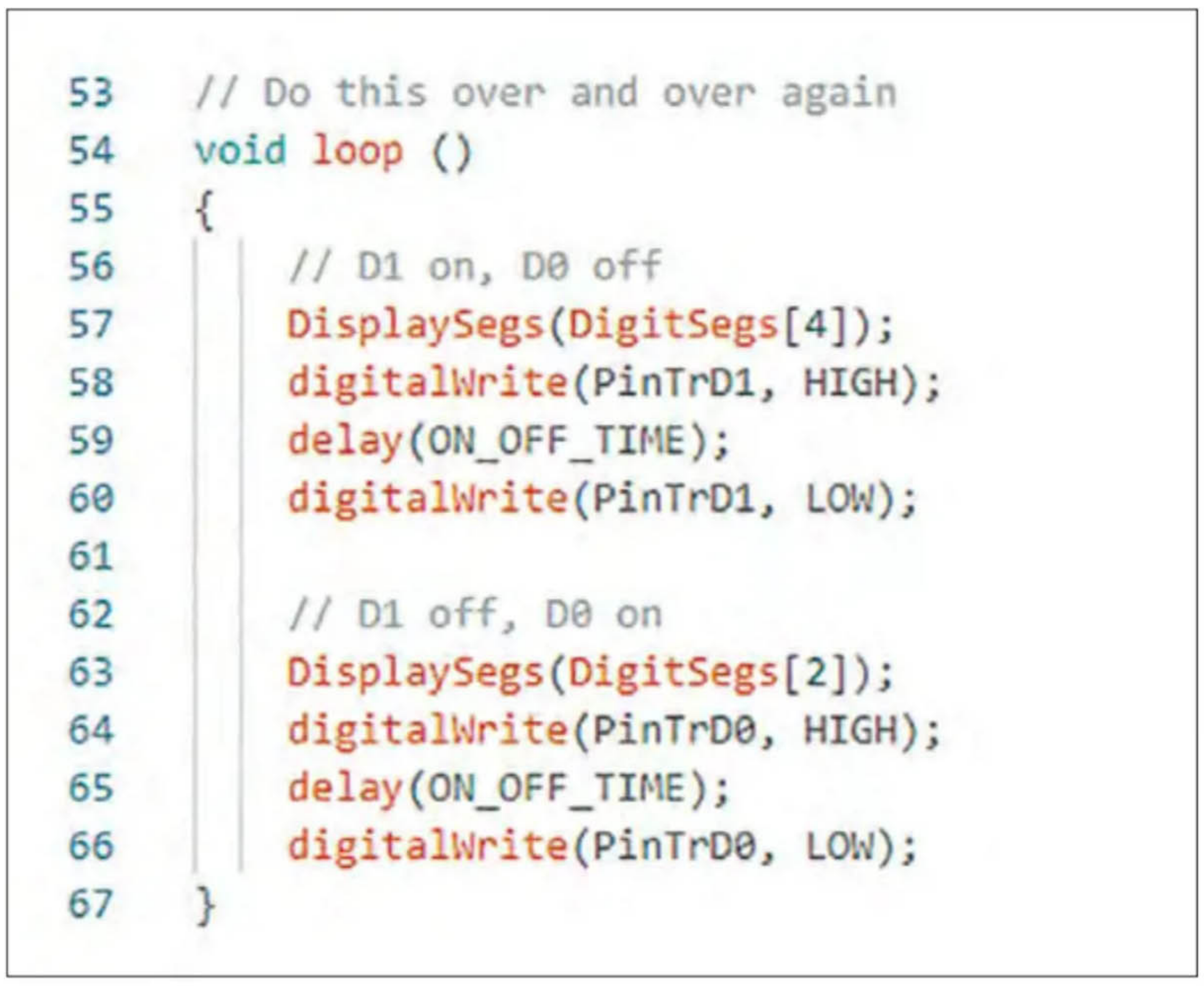
I replied that each segment in our 7-segment displays requires a current-limiting resistor. So… eight segments a display… two displays… sixteen resistors. Joe responded that he agreed… in principle. However, he then pointed out that since only one of our displays is going to be on at any time, we can therefore make do with only a single set of resistors.

O-M-G. I feel like an old fool (but where are we going to find one at this time of the day?). What this means is that we can remove one set of resistors and simplify our wiring from its current layout (Fig.7a) to a more minimalist interpretation (Fig.7b). Just to make sure we're all tap-dancing to the same skirl of the bagpipes; I've updated our master drawing (file **CB-May24-03.pdf**).

Hang on. Maybe I should have mentioned all this at the beginning of this column before you implemented our original wiring scheme yourself. Oh well, it's too late now. Once again, we can consider this to be a teachable moment. And, once again, you're welcome.

Both displays together

When we eventually get to present the time on our clock, we don't want to display the most-significant digit (MSD) on display D1 followed by the least-significant digit (LSD) on display D0 with only one digit visible at a time. What we really want is to have both of our displays presenting values at the *same* time.



```
// Do this over and over again
void loop ()
{
    // D1 on, D0 off
    DisplaySegs(DigitSegs[4]);
    digitalWrite(PinTrD1, HIGH);
    delay(ON_OFF_TIME);
    digitalWrite(PinTrD1, LOW);

    // D1 off, D0 on
    DisplaySegs(DigitSegs[2]);
    digitalWrite(PinTrD0, HIGH);
    delay(ON_OFF_TIME);
    digitalWrite(PinTrD0, LOW);
}
```

Listing 4a. The `loop()` function for second test.

We know we can't actually achieve this because – with our current setup – only one of our displays can physically be active at any time. However, due to persistence of vision (the optical illusion that occurs when the visual perception of an object does not cease for some time after the rays of light proceeding from it have ceased to enter the eye), if we swap back and forth between the displays fast enough, we can make it appear that both displays are presenting values simultaneously.

As a starting point, I've forked our earlier test program and made a few teensy-weensy modifications (file **CB-May24-04.txt**). In fact, the only changes occur in our `loop()` function, as illustrated in Listing 4a.

Just for giggles and grins, I've decided to present the number 42, with the 4 and 2 appearing on displays D1 and D0, respectively. As before, our `ON_OFF_TIME` definition is still set to 1000, which equates to 1000 milliseconds (ms).

So, we start by seeing the '4' for one second, then the '2' for one second, and then we do it all again. Now, let's change the value associated with `ON_OFF_TIME` to be 100 (that's 1/10 of a second) and reload the program into the Arduino. In this case, we can sort of see both digits at the same time, but accompanied by a lot of annoying flickering. How about we change the value associated with `ON_OFF_TIME` to be 10 (that's 1/100 of a second).

Wow! Both digits appear to be on at the same time without any observable flickering (Fig.8). 'I love it when a plan comes together,' as fearless frontrunner Hannibal Smith of A-Team fame famously said.

'42?' I hear you say… well, just take a look here: **https://bit.ly/pe-nov21-42**

Blinded by the light

Although the song *Blinded by the Light* was originally written and recorded by Bruce Springsteen, my favorite version is the one performed by Manfred Mann's Earth Band, but we digress…

As we shall soon see, there are more factors at play here than at first meet the eye (no pun intended). Depending on who you are talking to, our eyes and brains retain a visual impression for somewhere between 1/30 and 1/60 of a second. Let's say 1/50 second, which equates to 20ms. Known as 'persistence of vision,' this explains why we no longer perceive any flickering in our displays, each of which is now on for 10ms and off for 10ms.

But wait, there's more, because if we look at our displays, which are currently presenting 42, they appear to be running at full brightness to our eyes, even though we know that each display is active only half of the time. How can this be?

Well, one reason is that the human eye is incredibly sensitive over a wide dynamic range from starlight to daylight. Even within a single scene, the eye can perceive a dynamic range of up to 100dB, which equates to a brightness ratio of 100,000:1. Thus, one reason our displays appear to be so bright is that we have nothing to compare them to. I'm sure we would be able to detect some difference if we compared them to a third display running at full brightness 100% of the time, but that's not an issue here.

The technical term for what we've been doing with our displays is 'multiplexing,' which basically means that not all displays are on at the same time. Suppose we wished to add two more displays, thereby allowing us to present both hours and minutes (HH:MM) at the same time. If we were to extend our multiplexing technique, then each display would be active for only 1/4 of the time.

At this point, we would probably become aware that our displays are not as bright as we would prefer. Also, since each display would now be on for 10ms and off for 30ms (assuming we stick with our `ON_OFF_TIME` definition set to 10) we may start to see some flickering.

One solution to the flickering is to increase the refresh rate, perhaps changing the value associated with `ON_OFF_TIME` to 5ms (1/200 of a second) or even 1ms (1/1000 of a second).

With respect to the dimming of our multiplexed displays, one possibility is to increase the current being fed to each of the display segments. As a reminder, an Arduino Uno's pins prefer to sink or source up to 20mA. They can handle up to 40mA, but only for short periods of time. Thus, if we wanted to supply more than 20mA for sustained periods of time, we would use the Arduino's

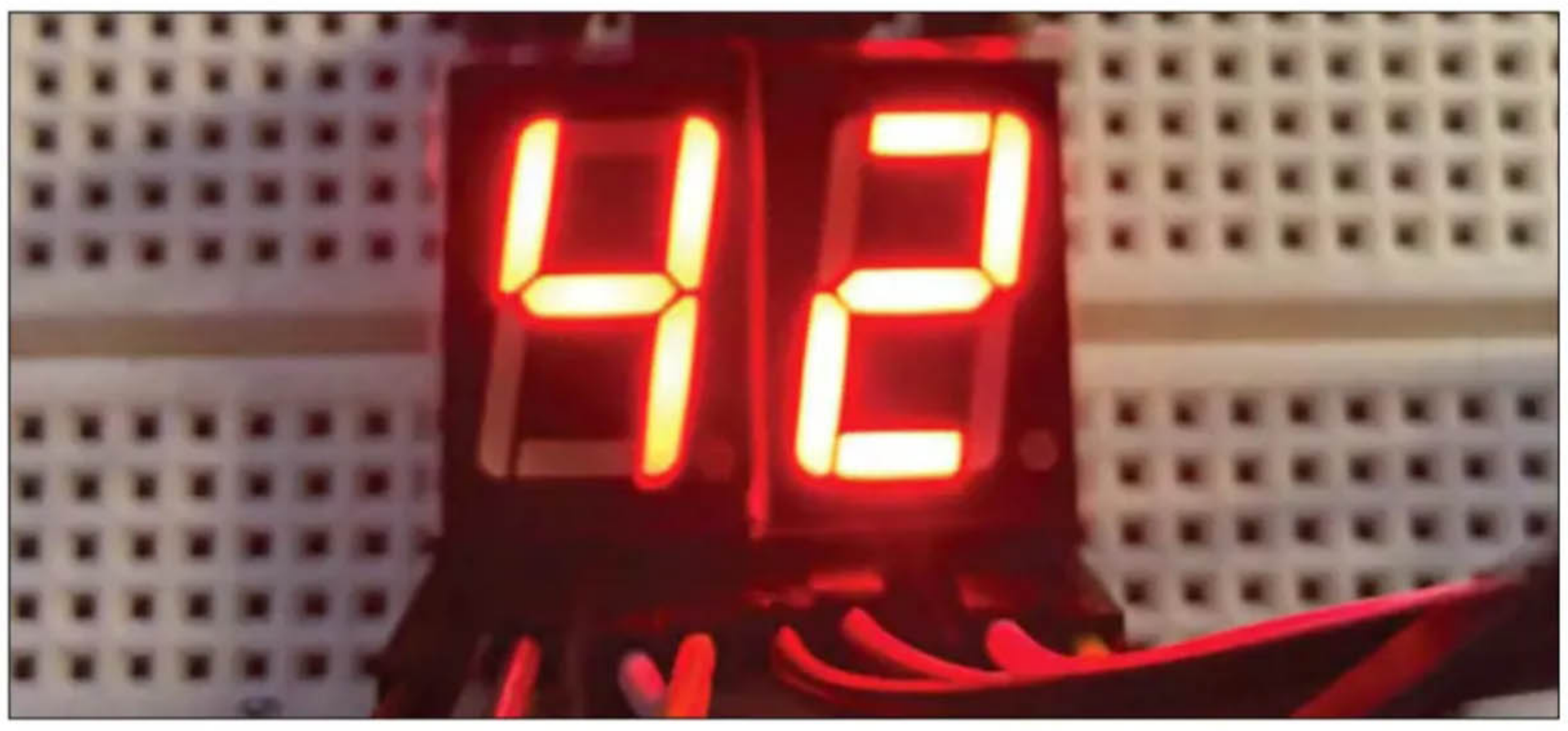


Fig.8. I think we've found the answer.

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

Components from Part 1

LEDs (assorted colours)	**https://amzn.to/3E7VAQE**
Resistors (assorted values)	**https://amzn.to/3O4RvBt**
Solderless breadboard	**https://amzn.to/3O2L3e8**
Multicore jumper wires (male-male)	**https://amzn.to/3O4hnxk**

Components from Part 2

7-segment display(s)	**https://amzn.to/3Afm8yu**

Components from Part 5

Momentary pushbutton switches	**https://amzn.to/3Tk7Q87**

Components from Part 6

Passive piezoelectric buzzer	**https://amzn.to/3KmxjcX**

Components for Part 9

SW-18010P vibration switch	**https://bit.ly/46SfDA4**

Components for Part 10

Breadboard mounting trimpots	**https://bit.ly/3QAuz04**

Components for Part 12

Light-Dependent Resistor	**https://bit.ly/3S2430m**

Components for Part 13

BC337 NPN Transistor	**https://bit.ly/40xAgyS**

Components for Part 14

HC-SR04 Ultrasonic Sensor	**https://bit.ly/49AMBq4**

Components for Part 15

Real-Time Clock (RTC)	**https://bit.ly/3S9OjHl**

pins to control transistors that could handle higher current values.

When it comes to LEDs, the relationship between current and luminous intensity is reasonably linear; that is, 2x the current results in 2x the luminous intensity. So, does this mean that 2x the current results in 2x the brightness? That depends on whether we are talking about actual brightness as measured by an electronic instrument, in which case the answer is 'Yes,' or perceived brightness as seen by the human eye, in which case the answer is 'No.' This is because the eye's response to signal intensity is non-linear.

At this point, I can imagine you saying, 'Hang on a minute. We are using 7-segment LEDs whose data sheets specify a 'forward voltage drop' of 2V and a 'maximum continuous (sustained) forward current' of 20mA. Also, we are using 150Ω current-limiting resistors to provide our 20mA maximum. So, how can we increase the current?' I'm glad you asked.

If we look more closely at the data sheet, we may also see a 'maximum pulse current' specification of 100mA, for example (this value will have associated qualifiers, like a maximum active duration and a maximum duty ratio).

Let's perform a thought experiment. Suppose we take two segments on one of our displays. Assume we connect a 150Ω resistor to one segment, thereby limiting its current to 20mA, and we set this segment running 100% of the time. Also assume we connect a 75Ω resistor to the second segment, thereby allowing a current of 40mA, and we turn this segment on and off very quickly such that it's active only 50% of the time.

Since the two segments' average currents are identical, will their perceived brightnesses also be identical? Let's say 'Yes,' because it's almost true, and we really don't want to wander any further into the weeds.

Is it a good idea to boost the current in this way? It depends. On the one hand, it provides a solution to a problem. On the other hand, using high current pulses ages LEDs and causes them to dim faster, which may or may not be an issue depending on the expected life of the product.

More problematic is what will happen if the microcontroller crashes or freezes (locks up) with one or more of the LEDs on. This may also occur when the user performs some action like activating a menu subsystem, which means the programmer must account for all such possibilities. In this case, the LEDs won't last long at all. This is the sort of thing professional electronic engineers must consider and design around.

Happily, this technique – boosting the current – provides one more example of 'that's interesting' and 'it's not our problem' because we aren't going to use it.

It's almost time

Finally, nearly, it's almost time for us to start displaying the time, but first…

You may feel free to call me an old fussy-fuddy-duddy if you will but – before we proceed – since we've made so many modifications to our prototype, I think it's a good idea to make sure we haven't &%**$#$@ anything up in the process (forgive my use of the engineering vernacular).

I just loaded one of the programs we created earlier (*PE*, March 2024). This is the one that loops around reading the date and time from our real-time clock (RTC) and displaying these values in our Serial Monitor (file **CB-May24-05.txt**).

It still works! Hurray!

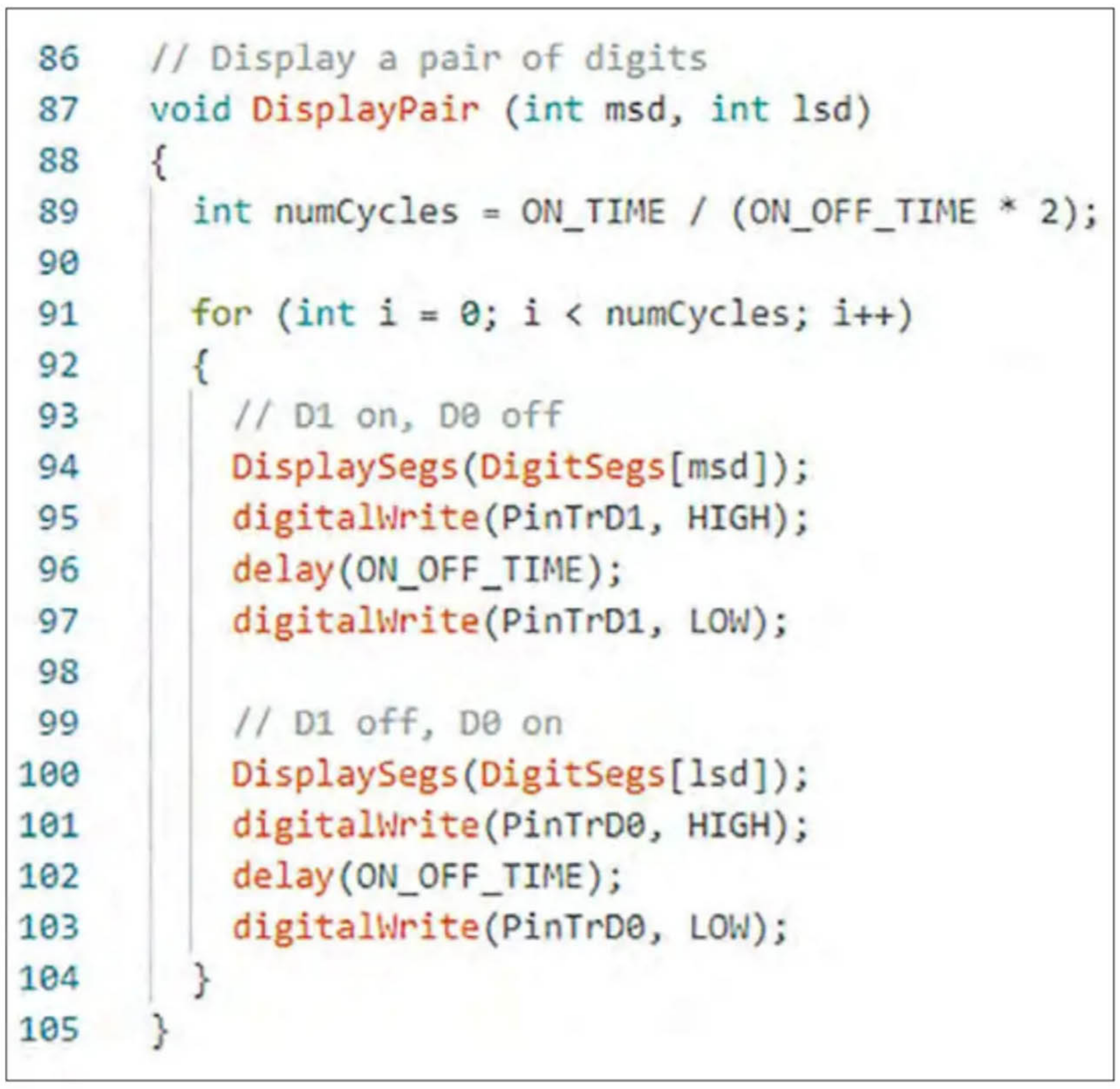
The time has come!

To be honest, after all we've been through, the next part may seem somewhat anticlimactic… except for the fact that *it works*, of course.

What we are going to do is fork the final program we created in the previous column (*PE*, April 2024). This was the one that looped around reading the time from the RTC and then displaying the 2-digit hour and 2-digit minute values as a series of four digits on our single 7-segment display.

We are going to augment this program with the ability to present pairs of digits on our dual displays using the technique we developed above. This means we will be able to display the two hour digits followed by the two minute digits. The result is available for your delectation and delight (file **CB-May24-06.txt**).

All we need to know for the purpose of these discussions is that, in addition to `ON_OFF_TIME` being defined as 10, we've also defined `ON_TIME` as 360,

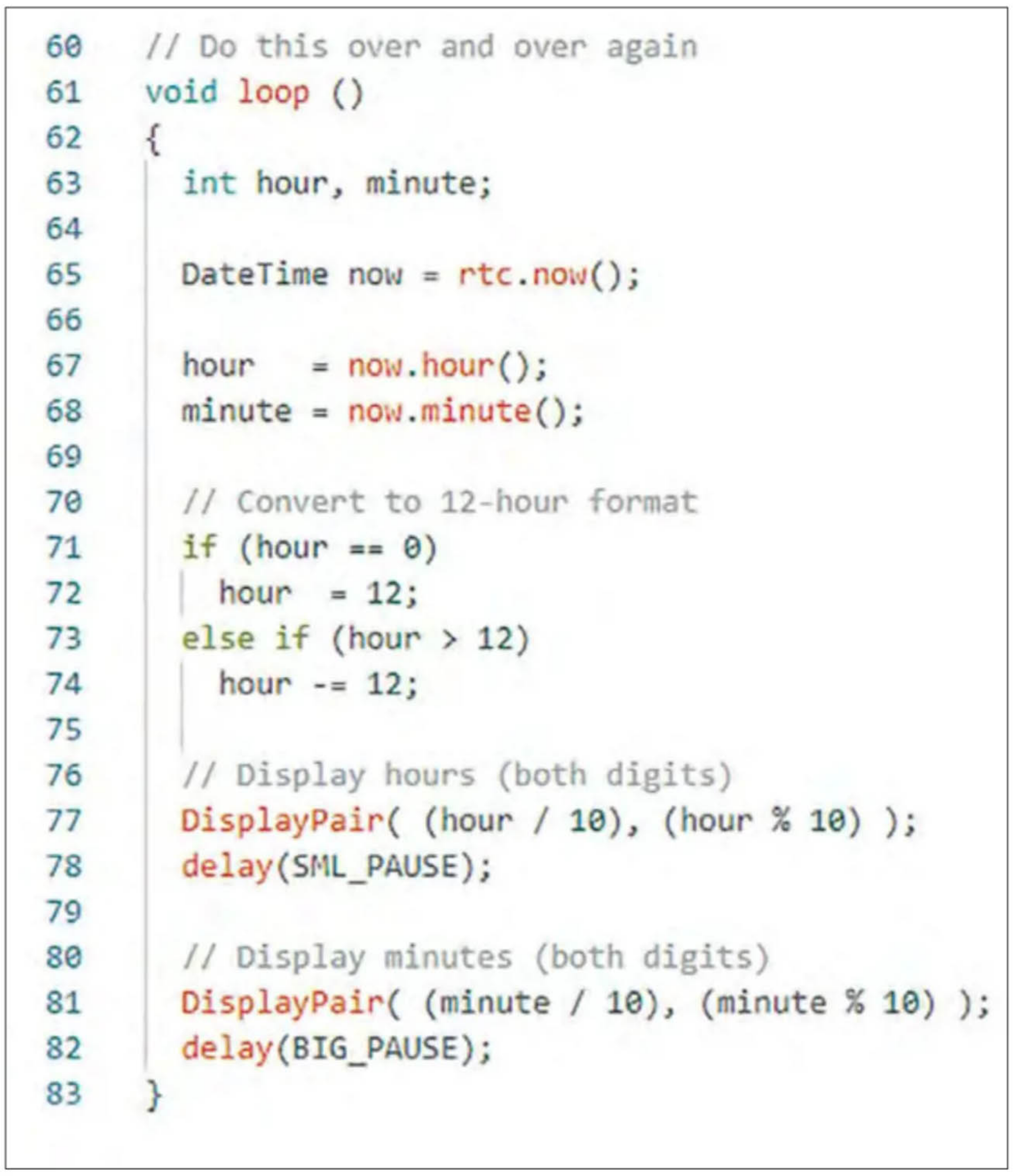


```
// Display a pair of digits
void DisplayPair (int msd, int lsd)
{
  int numCycles = ON_TIME / (ON_OFF_TIME * 2);

  for (int i = 0; i < numCycles; i++)
  {
    // D1 on, D0 off
    DisplaySegs(DigitSegs[msd]);
    digitalWrite(PinTrD1, HIGH);
    delay(ON_OFF_TIME);
    digitalWrite(PinTrD1, LOW);

    // D1 off, D0 on
    DisplaySegs(DigitSegs[lsd]);
    digitalWrite(PinTrD0, HIGH);
    delay(ON_OFF_TIME);
    digitalWrite(PinTrD0, LOW);
  }
}
```

Listing 6a. (above) Our new `DisplayPair()` function.



```
// Do this over and over again
void loop ()
{
  int hour, minute;

  DateTime now = rtc.now();

  hour   = now.hour();
  minute = now.minute();

  // Convert to 12-hour format
  if (hour == 0)
    hour  = 12;
  else if (hour > 12)
    hour -= 12;

  // Display hours (both digits)
  DisplayPair( (hour / 10), (hour % 10) );
  delay(SML_PAUSE);

  // Display minutes (both digits)
  DisplayPair( (minute / 10), (minute % 10) );
  delay(BIG_PAUSE);
}
```

Listing 6b. (right) Our modified `loop()` function.

SML_PAUSE as 180, and BIG_PAUSE as 720. Also, we've added our PinTrD0 and PinTrD1 declarations so we can control our transistors.

The first change we've made is to add a new function called DisplayPair() as illustrated in Listing 6a. The role of this function is to display a pair of digits for a specified amount of time (this is our ON_TIME). It doesn't take long to realise that the body of our new function is almost identical to the contents of the loop() function in our previous test (Listing 4a). In fact, there are only two significant differences.

The first difference is seen in Lines 93 through 103. As opposed to displaying fixed values of 4 and 2 on D1 and D0, respectively, we are instead displaying integer variables called msd and lsd, whose values are passed into the function.

The second difference is that, as opposed to the original loop() function running forever, we are using the for() loop that starts on Line 91 and ends on Line 104 to limit the duration of the display to a specific number of cycles, as defined by the integer variable numCycles.

The value assigned to numCycles is calculated on Line 89. From our previous experiments, we know we can achieve a flicker-free presentation by swapping back and forth between displays, with each display being on for ON_OFF_TIME (which we've set to 10ms, or 1/100 of a second). This means that a complete display cycle (D1 then D0) will take (ON_OFF_TIME * 2) = 20ms.

Since the total time we wish to display this pair of digits is ON_TIME (which we've defined to be 360ms), then our numCycles will equate to 360 / 20 = 18. The reason for doing things this way, as opposed to simply plonking a value of 18 in our for() loop, is that it makes it easy for us to experiment with different values.

Next, let's turn our attention to our new loop() function, as illustrated in Listing 6b. Lines 63 through 74 are identical to the program we created in our previous column. This is where we read the current date and time from our RTC and boil things down to the hour and minute we wish to display.

As you may recall, we are using the RTC in its default 24-hour mode, in which the hours are numbered from 0 to 23, and then converting this into a 12-hour format, in which the hours are numbered 12, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11. Meanwhile, the minutes are numbered from 0 to 59.

On Line 77 we call our new DisplayPair() function, passing in two arguments in the form of the most-significant and least-significant hours digits. On Line 78 we pause for a short delay. On Line 81 we call our DisplayPair() function again, this time passing in the most-significant and least-significant minutes digits. Finally, on Line 82 we pause for a longer delay.

I'm sitting here watching my dual display presenting the time in the form:

HH… MM… … … HH… MM… … … HH… MM… … … and it looks great!

Next time…

We are getting closer and closer to creating a 4-digit display device. As the next step along the way, we are going to refresh our minds as to the concept of binary coded decimal (BCD), and then investigate various deployments of BCD-to-7-segment

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

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AUDIO OUT

By Jake Rothman

Back to the buffers – Part 4

This month, we'll wrap up the series on discrete op amp/buffer designs. The complexity of a full discrete op amp is not really required for a buffer and the simple three-transistor circuits given (*PE*, April 2024, Fig.24, Fig.27) are usually sufficient. However, sometimes op amp characteristics, such as a low output offset are occasionally needed. The high open-loop gain of a full op amp (discrete or monolithic) also enables a very low output impedance to be obtained. There are some expensive dedicated buffer chips available, such as the LM302, which employs 18 transistors. So, I thought a 'halfway-house' discrete solution based on an op amp input stage with the voltage amplifier stage (VAS) omitted would be worthy of some R&D.

Op amp buffer design

My resulting design is a two-stage op amp, sometimes called a 'Schlotzaur circuit'. It has an open-loop gain of around 6000 if constant current loads are used. To start, the discrete op amp board from the October 2023 article was used with a long-tailed pair (LTP) stage followed by a class-A emitter follower. A possible problem with this topology using 100% negative feedback, is that the operating level of the input stage is the same as the output. Indeed, this was a problem, with the distortion level increasing in proportion to the output voltage, as shown later.

Development trials and tribulations

Originally, the output stage of the first discrete op amp which I used as a buffer just consisted of an emitter follower (TR3) and current sink running at 10mA (TR7) – see Fig.35. This was adequate for high impedance loads, but not for full output into 600Ω. The solution was a three-transistor follower and a modulated current source. The first circuit tried was to simply connect the three-transistor buffer to the op amp input stage. A successful circuit design strategy is to start by combining circuit blocks you already know work. If it doesn't work, it's easier to find the fault. There was a hard offset upon turn-on because I forgot that the omitted voltage-amplifier stage was inverting. To get round this, the negative feedback had to be applied to the *non*-inverting terminal OA+ on the input stage. Guess what? It still didn't work. Then I remembered the current mirror had to be turned round as well. One side of the mirror is output and the other, the diode-connected transistor side (TR5 on the original op amp circuit (*PE*, October 2023, Fig.15)), is for current sensing. Having done this necessary 'flipping', the circuit worked. Next, I needed to do some optimisation.

Oscillation

As is usual with new circuits with negative feedback, it oscillated when first turned on. It was barely visible on the scope as a thicker trace, but very apparent on the distortion analyser, with a reading of 0.02% THD+N at $1V_{rms}$ (total harmonic distortion plus noise). I knew from before that both circuit blocks were capable of at least ten-times better distortion. One reason I pursue vanishingly low distortion figures in my circuits, even though the improvements may be inaudible, is to clear the view for other problems and non-linearities that can hide behind a high general THD floor. These can be low-level oscillations or the subtle low-frequency rise in THD that occurs with capacitors, for example.

To fix the oscillation, I placed a capacitor (C_{Comp}) across the collectors of the long-tailed pair. I used 470pF out of the 'mixed cap' drawer which fixed the oscillation problem. I then checked for slewing distortion which occurred at a too low a frequency of 40kHz, so I then reduced the capacitor to 150pF – but then some other unwanted high-frequency signal appeared. Fortunately, this was not an oscillation, but 470kHz RF noise emitted from a new Metcal soldering iron I had recently started using. Unfortunately, this new problem also had me going round in circles for a couple of days after sudden rises in distortion on various amplifiers I was testing. The problem was solved by moving the soldering iron away from the test circuit, at which point I was relieved to determine that the 150pF

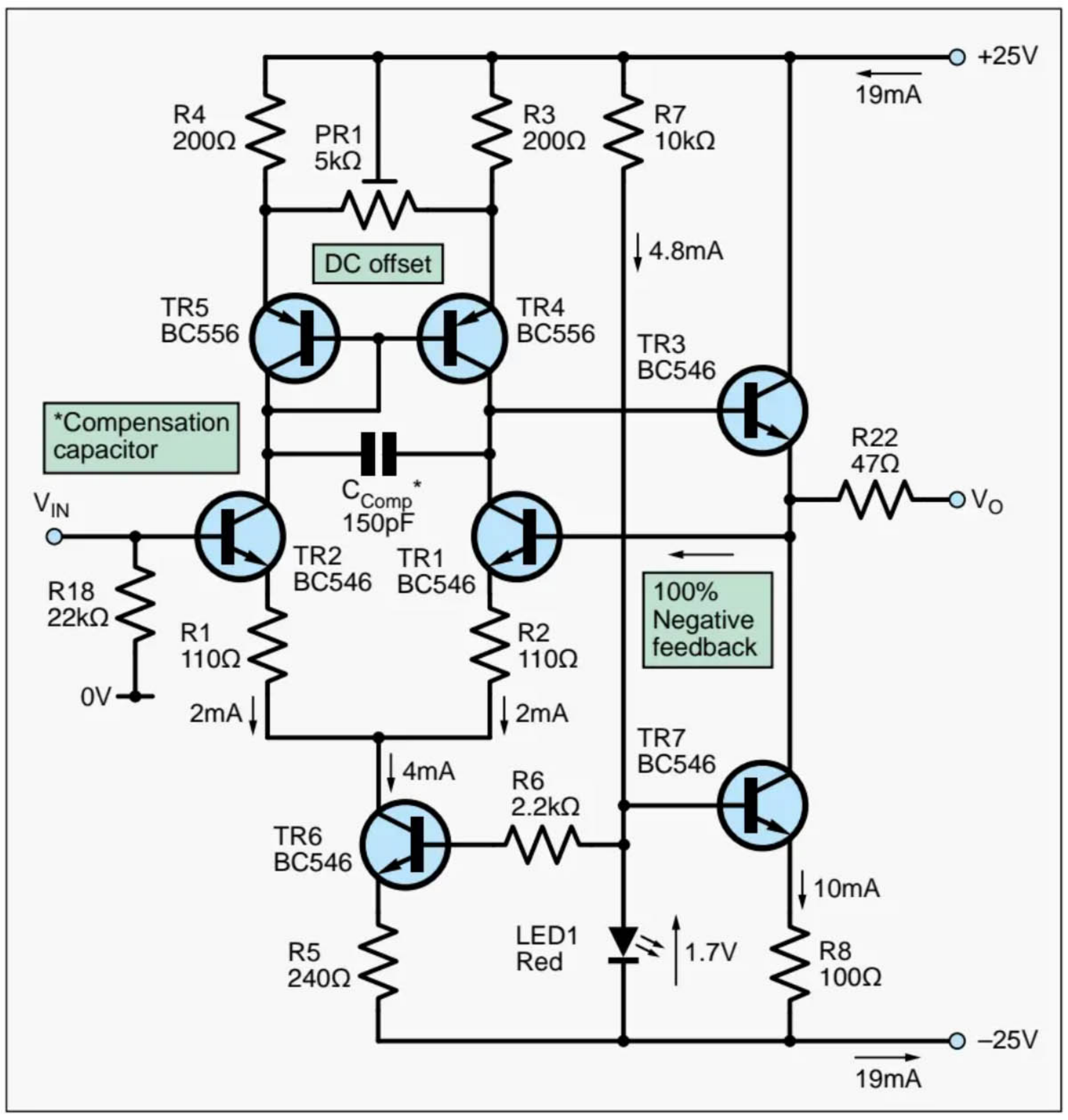


Fig.35. Initial discrete op-amp-style buffer. This is reconfigured to compensate for the omission of the inverting VAS stage. Note component numbering refer to the discrete op amp PCB (*PE*, November, 2023).

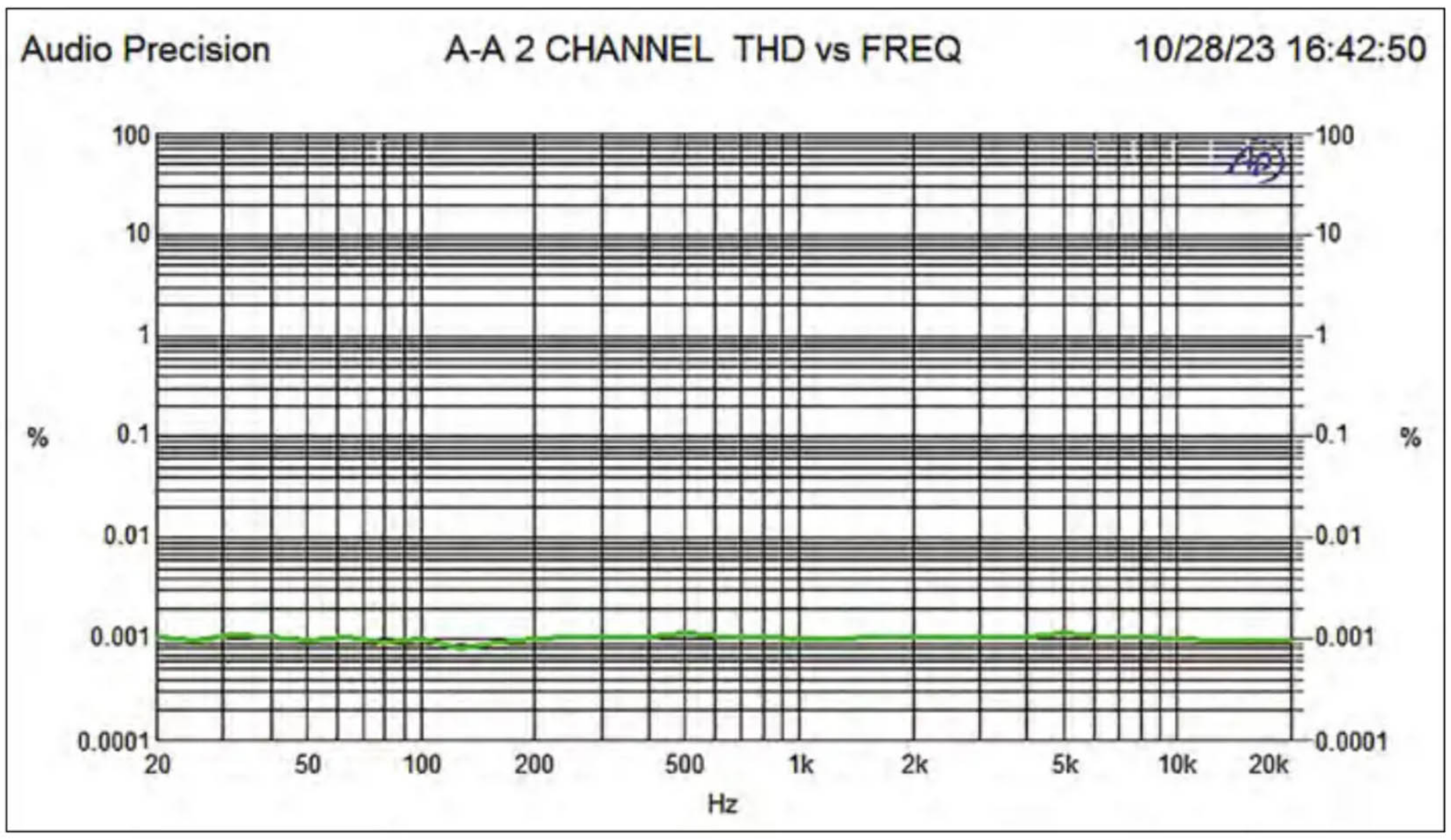


Fig.36. The effect of using an output MOSFET for the JFET discrete op-amp-based buffer circuit was to reduce the distortion compared to a Darlington (TR3) in Fig.37.

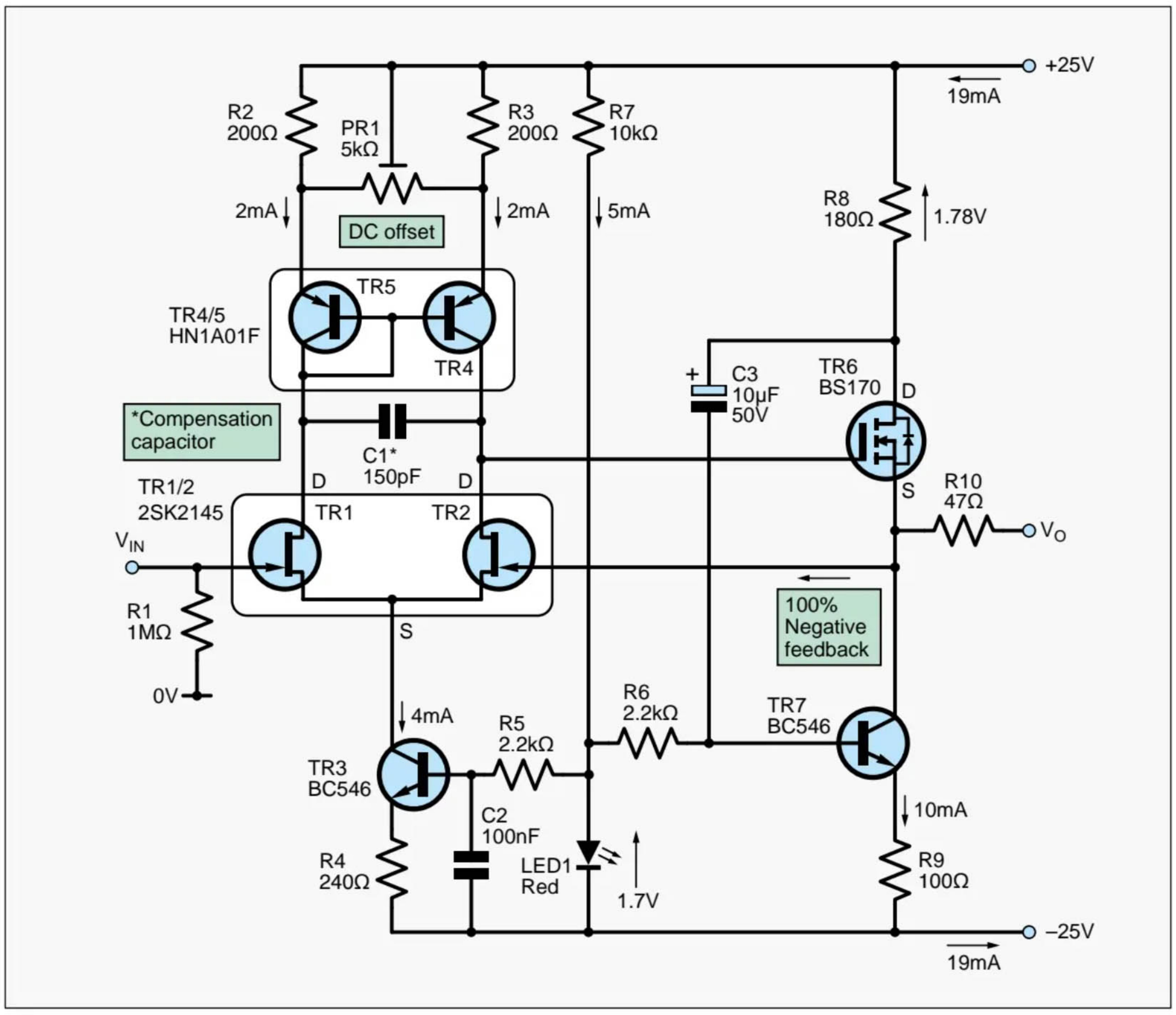

+25V
19mA
R2
200Ω
PR1
5kΩ
R3
200Ω
R7
10kΩ
2mA
DC offset
2mA
5mA
R8
180Ω
1.78V
TR5
TR4/5
HN1A01F
TR4
*Compensation capacitor
C1*
150pF
C3
10µF
50V
TR6
BS170
D
S
R10
47Ω
VO
TR1/2
2SK2145
D
D
TR1
TR2
VIN
R1
1MΩ
0V
S
100%
Negative feedback
4mA
TR3
BC546
R5
2.2kΩ
R6
2.2kΩ
TR7
BC546
C2
100nF
LED1
Red
1.7V
R4
240Ω
10mA
R9
100Ω
–25V
19mA

Fig.37. Final discrete MOSFET op-amp-based buffer circuit with JFET input and MOSFET output. (Note: components renumbered, coupling/decoupling capacitors omitted.)

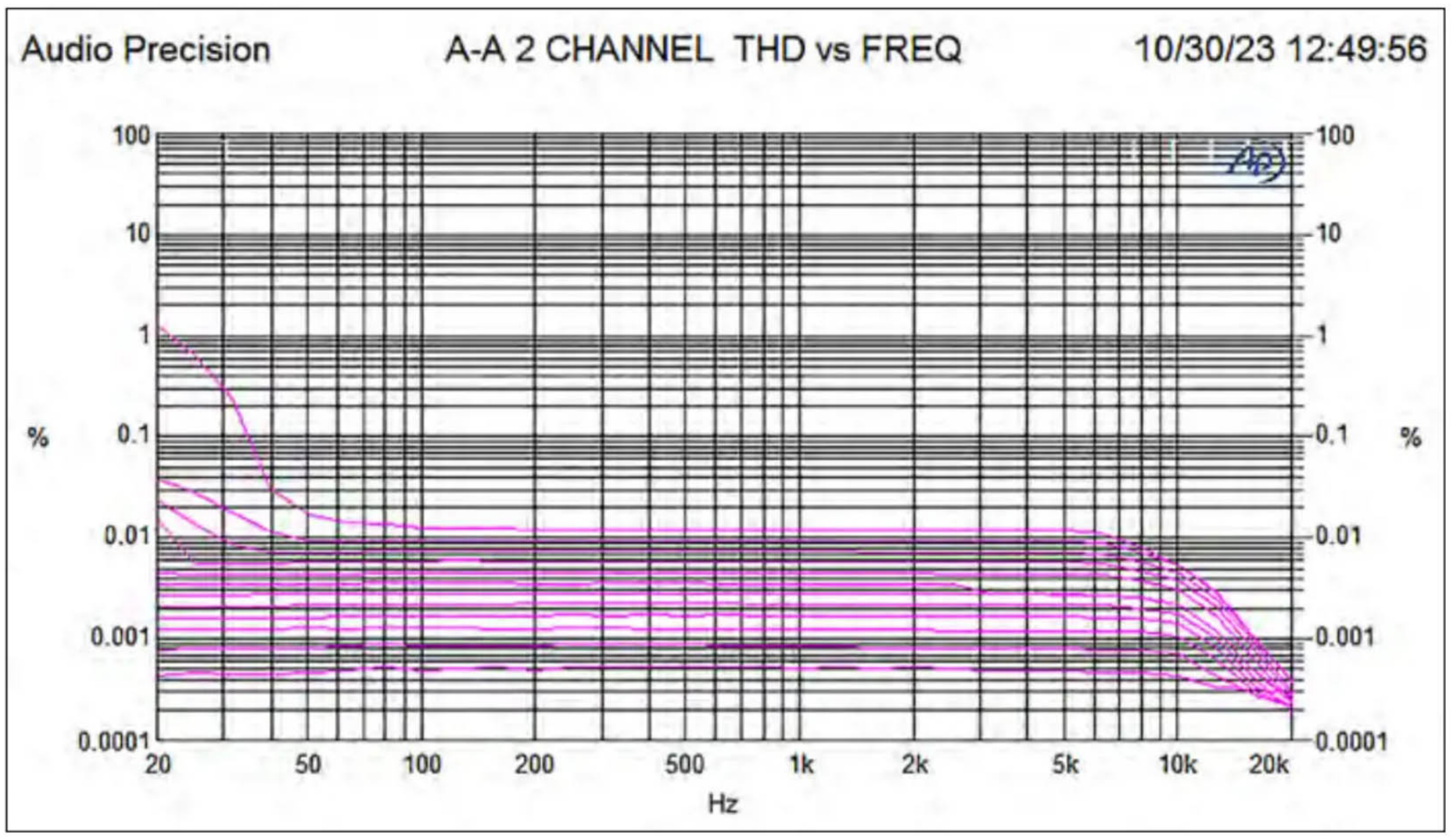


Fig.39. Increasing the output level for the FET (JFET input, MOSFET output) op amp buffer in Fig.37 in 1V$_{rms}$ steps to 12V$_{rms}$ into a 600Ω load increases the distortion as expected. Note the rapid rise of distortion at 20Hz to 1.3% at 12V due to the 10µF 50V tantalum bead modulation capacitor (C3) being stressed. Changing this device to a 22µF 50V metal-cased tantalum reduced it to 0.025%.

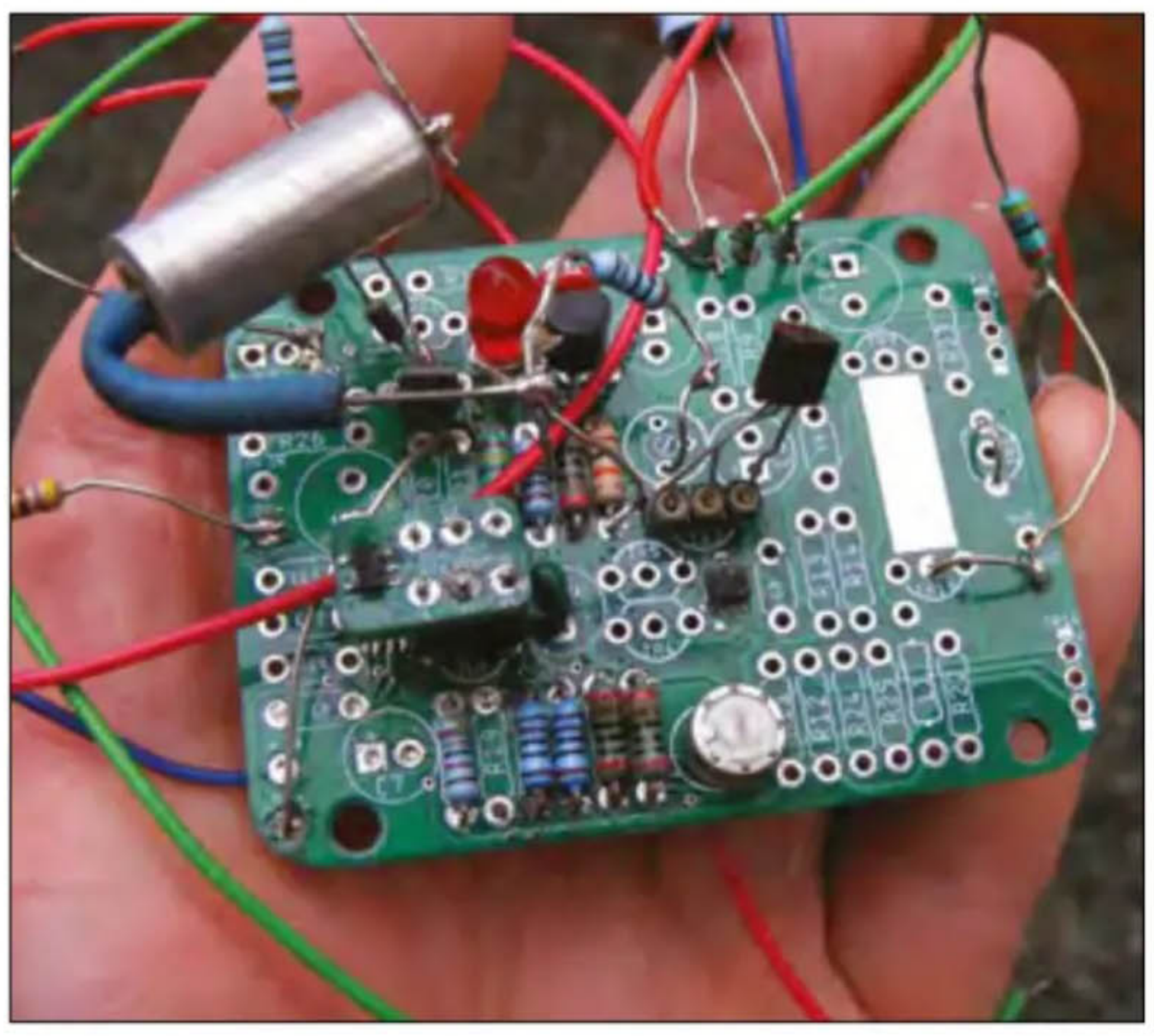


Fig.38. Building the MOSFET op-amp-based buffer on the discrete op amp PCB (*PE*, November, 2023). This is how prototypes can look. Note that individual devices can be plugged in to sockets for changing devices during testing.

capacitor was sufficient to fix the oscillation problem.

Another cause of 'raised distortion' was a bench power supply placed too close to the Audio Precision audio analyser. I found magnetic coupling between the power supply's large, laminated transformer and the audio analyser's output transformers. About 200mm clearance was required.

Since the output stage was enclosed in a negative feedback loop, I found the value of the sense resistor (R8, Fig.37) was much less critical for minimum distortion than in the three transistor circuits. I then set it for maximum output swing into a 600Ω load.

Next, I decided to run the input stage at double the current (2mA per each transistor) to increase the slewing, give greater drive to the output stage and to get more transconductance out of JFETs if these are used for the long-tailed pair.

Component selection

Following on from my experience with parts for the discrete op amp, I strongly suspcted dual transistors would give the best results – and they did. Using JFETs for the long-tailed pair revealed them to be more sensitive to loading from the output stage. I tried an MPSA29 Darlington transistor for the emitter follower (TR3) and the distortion dropped by 75% compared to a BC546B.

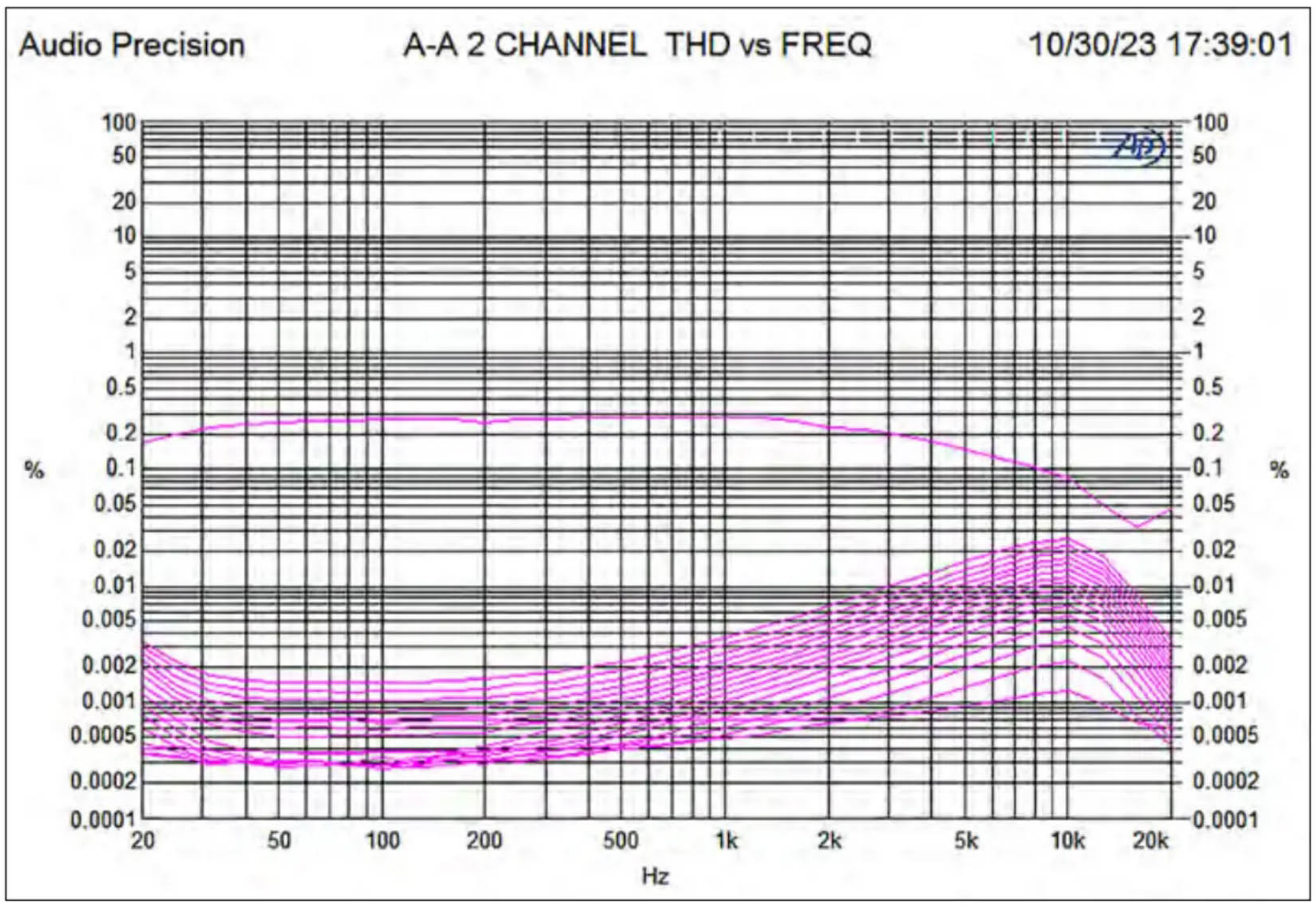


Fig.40. Using the original full discrete op amp as a buffer suffers from rising high-frequency distortion. Note that the top curve is for the output just before clipping at $17V_{rms}$.

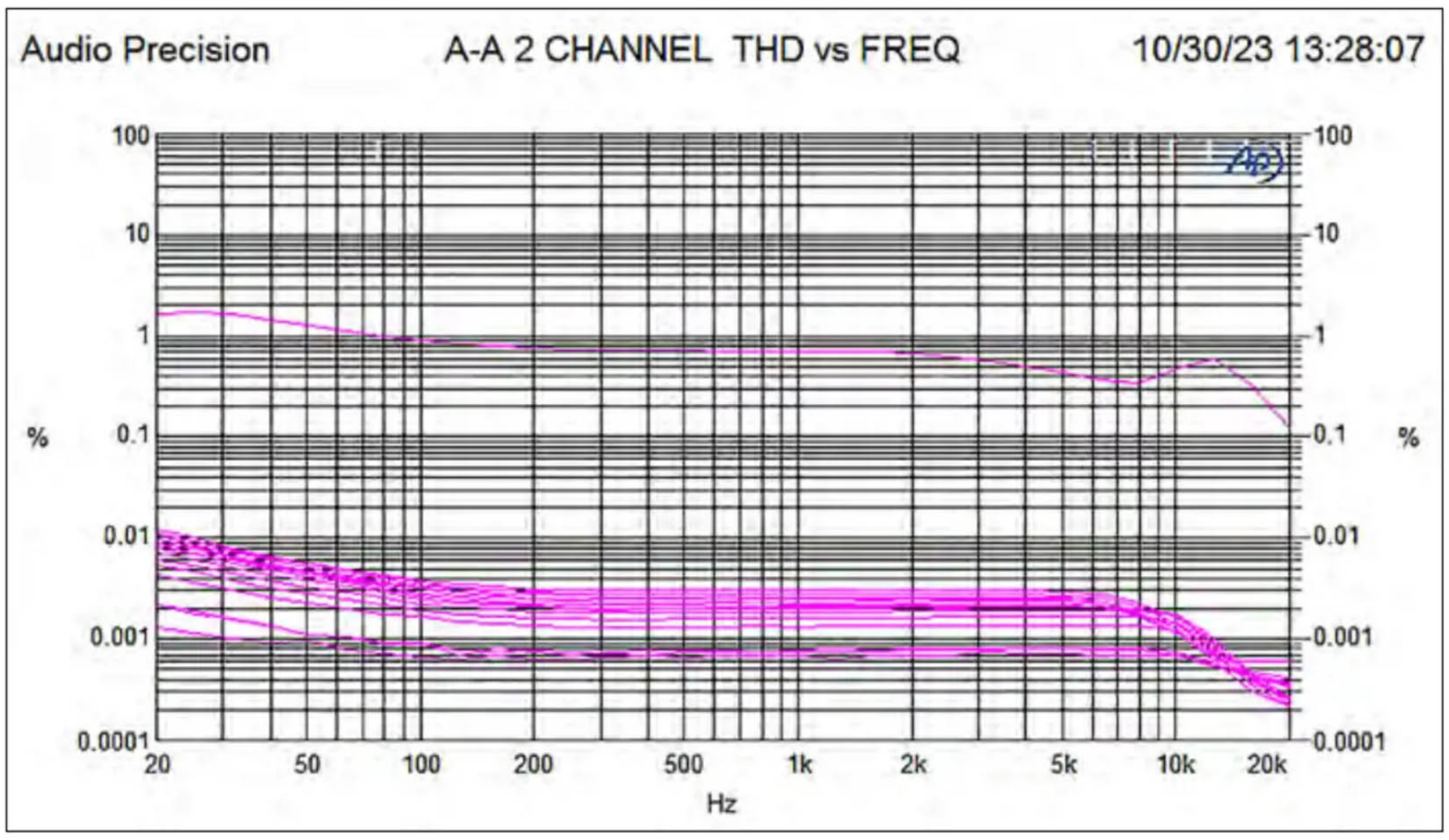


Fig.41. Distortion for three-transistor buffer just before clipping (Fig.24). These curves are taken in steps from 1V to $15V_{rms}$ into 600Ω. Clipping is just beginning to occur at $15V_{rms}$, hence the sudden jump in distortion.

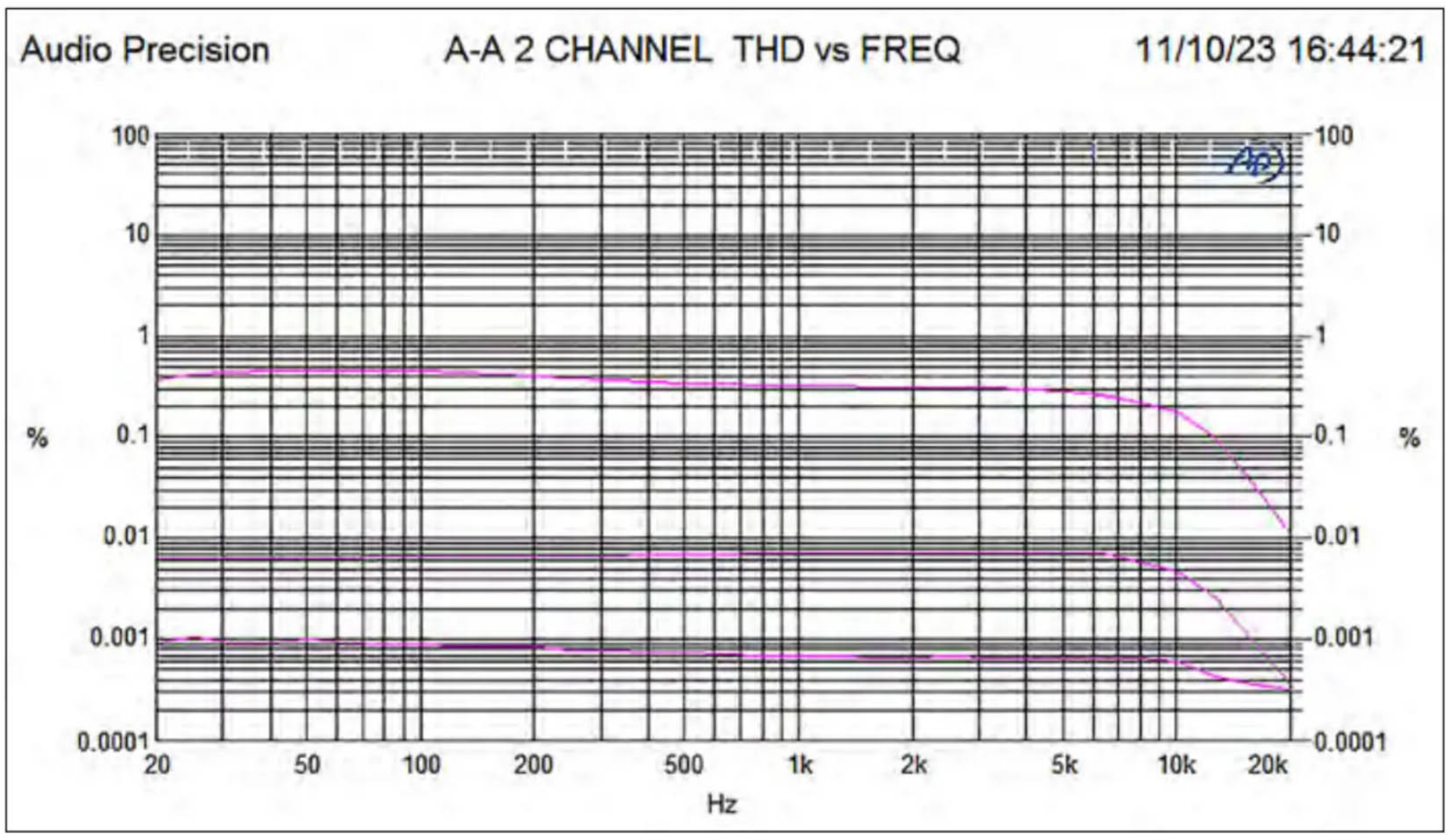


Fig.42. Distortion plot for JFET single-ended buffer in Fig.27 at $1V_{rms}$, $4V_{rms}$ and $8V_{rms}$ respectively.

However, some sort of curvature cancellation magic happened when I put in a BS170 MOSFET with current-sink modulation. Using this device the circuit achieved the excellent figure of 0.001% THD+N, as shown in Fig.36. My final circuit is shown in Fig.37, and the messy prototype construction of the discrete op amp PCB in Fig.38.

Distortion depression

However, this low distortion was only for an output signal of 1Vrms ($2.8V_{pk-pk}$) into 600Ω. I needed to check the distortion at different output levels all the way up to clipping. I increased the output level in $1V_{rms}$ steps on the Fig.37 FET op amp buffer giving the curves shown in Fig.39. What looked good at $1V_{rms}$ didn't look so good at higher test levels up to clipping. There was a rise in distortion at the low-frequency end at $12V_{rms}$ due to the modulation capacitor C8 getting stressed.

I then tested the original full discrete op amp (*PE*, October 2023, Fig.15) wired as a buffer with 100% negative feedback and this gave a large high-frequency (10kHz) distortion hump of 0.026% at $16V_{rms,}$ shown in Fig.40. This is because a lot of compensation capacitance is required to make this topology unity-gain stable. This causes a problem with slewing when driving the capacitance and there is little negative feedback at high frequencies left for output stage distortion reduction. It did give a large output of $17V_{rms}$ ($48V_{pk-pk}$) just beginning to clip with ±25V rails, $2V_{rms}$ more than the single-ended three transistor circuit for the same rail voltage.

Back to the three-transistor buffer

I then checked the three-transistor buffer circuit shown in Fig.24 which gave better performance than the op amp version at the higher test levels (above $1V_{rms}$), as shown in Fig.41.

I can't leave things alone and decided to replace R7 with a more stable constant-current source using a 1mA CRD (current-regulator diode). The distortion dropped by a third to 0.0015% at $8V_{rms}$ and the low-frequency distortion increase vanished. At $1V_{rms}$ the distortion was flat over the whole band at 0.0005%, a useful upgrade. Sadly, this was not so effective on the JFET version which also needed the sense resistor R8 adjusting to 470Ω. I was hoping this constant-current mod would reduce the distortion variation between different individual JFETs. It didn't. If I was a total obsessive, I would make R8 a preset adjustment tweaked for each individual JFET. Fig.42 shows the distortion at different levels produced

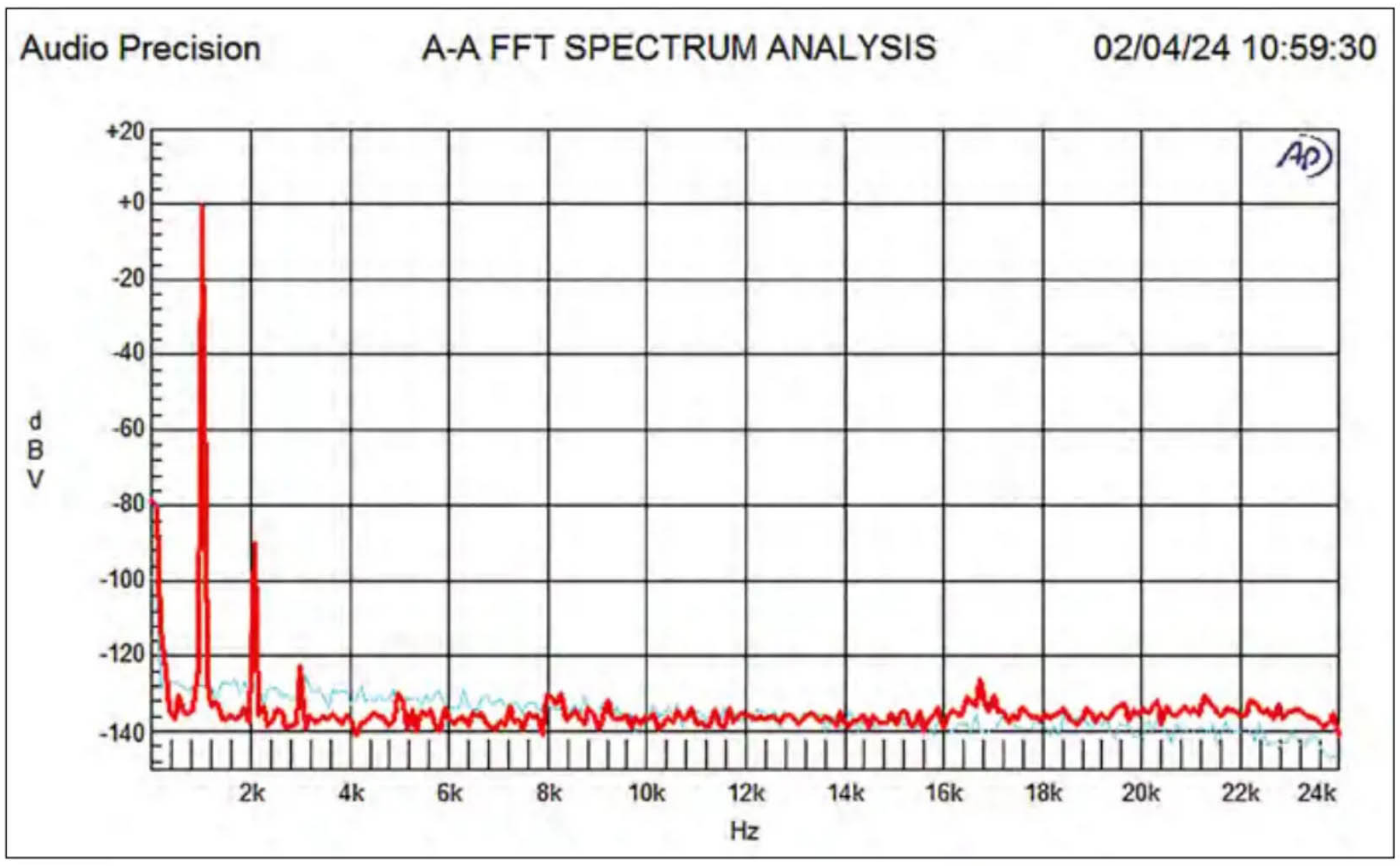


Fig.43. Spectrum of distortion harmonics produced by the single-ended JFET buffer in Fig.27 driven at 1kHz 0dB. Note the relatively large amount of second harmonic (2kHz) which is 90dB down relative to 1kHz. The third harmonic is 122dB down. Since it is a simple circuit with low feedback the higher harmonics are invisible, buried in noise.

by the JFET single-ended three-transistor buffer. However, the bulk of distortion generated is second harmonic, as shown in the spectrum analysis plot in Fig.43 produced using fast Fourier transform analysis. FFT is a useful feature of the Audio Precision analyser, TiePie scopes and various software packages. This type of distortion at this level is inaudible, but at high levels can even sound nice, so the variation between JFETs is nothing to worry about.

It's for real

It is possible to use simulation for this type of R&D and it is great for checking whether a circuit will basically work, avoiding the latch-up scenario I had earlier. However, I dislike simulation for distortion analysis because it tends to underestimate problems. Also, I've been doing practical circuits since I was 12 and I'm now 61, so I stick to what I'm good at! It takes me longer to input the schematic into LTSpice than it does to build it. I can pull out any component from my vast 'Cupboard-Based Programming Language' (CBPL, shown in Fig.44) quicker than downloading any component model on-line. When I need a simulation I can always get a friend with the necessary 10,000-hours practice time to do a skills swap with me. The catch with my CBPL method is that the file size is 1500 square feet. You need to have bought a house before 1995 or have had a big inheritance to install it.

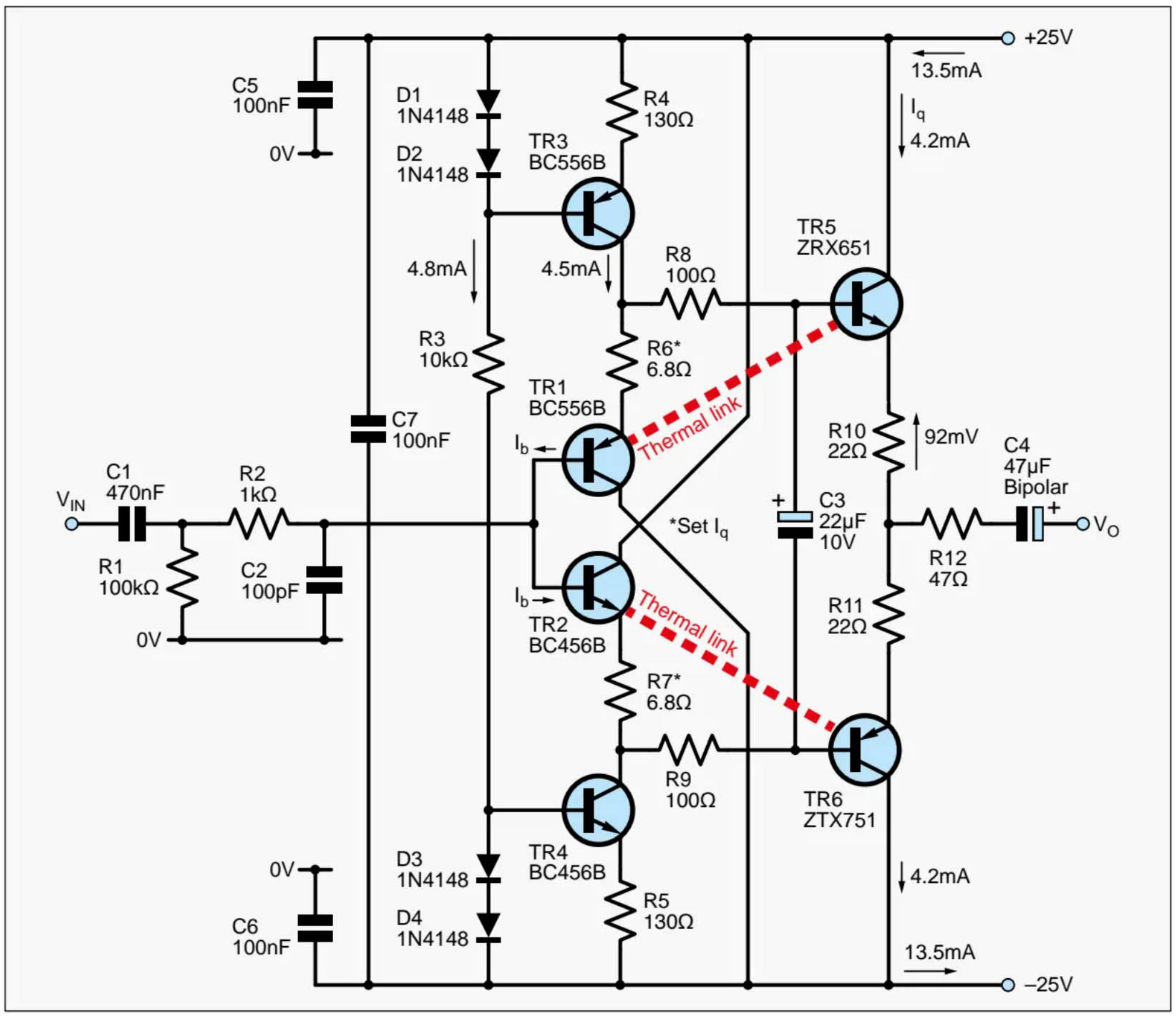
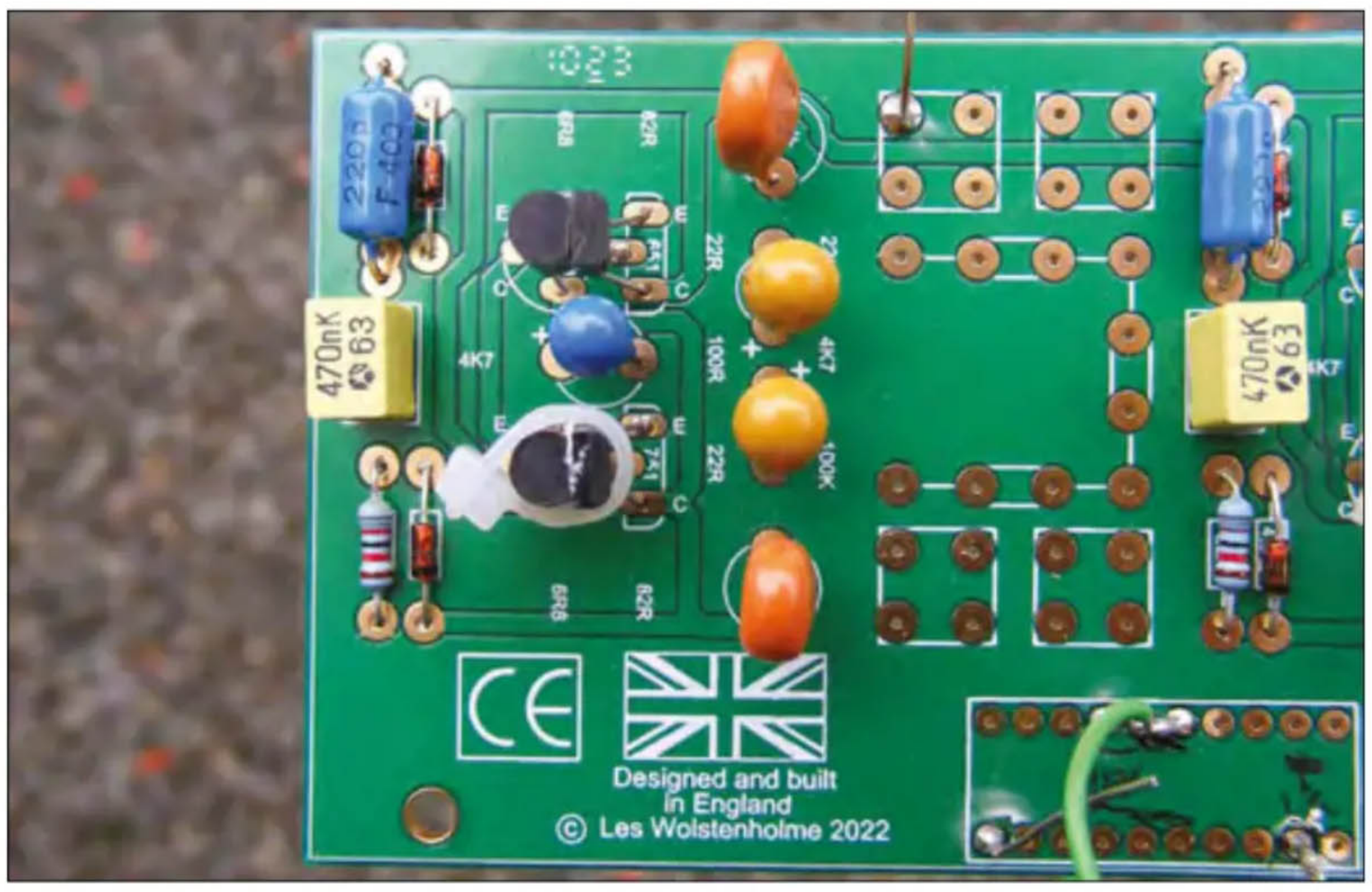

+25V
13.5mA
Iq
4.2mA
C5
100nF
0V
D1
1N4148
D2
1N4148
R4
130Ω
TR3
BC556B
TR5
ZRX651
4.8mA
4.5mA
R8
100Ω
R3
10kΩ
R6*
6.8Ω
TR1
BC556B
Thermal link
C7
100nF
Ib
R10
22Ω
92mV
C4
47μF
Bipolar
VIN
C1
470nF
R2
1kΩ
*Set Iq
C3
22μF
10V
R12
47Ω
VO
R1
100kΩ
C2
100pF
0V
Ib
TR2
BC456B
Thermal link
R11
22Ω
R7*
6.8Ω
R9
100Ω
TR6
ZTX751
TR4
BC456B
0V
D3
1N4148
D4
1N4148
R5
130Ω
C6
100nF
4.2mA
13.5mA
–25V

Fig.45. 'Diamond' buffer. An unusual circuit with two parallel, but opposite polarity input emitter follower stages. These then drive a complementary class-AB emitter-follower output.

Fig.44. 'Cupboard based programming language' for analogue circuits. This shelf of passive components comprises 650 Farnell plastic drawers alone. (These cost more than the parts in some cases!)


Designed and built in England
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470nK 63
470nK 63
22R
100R
4K7
100K

Fig.46. This Avondale Audio active crossover board uses four diamond buffers with a similar proprietary circuit to Fig.45. The transistors are thermally coupled to ensure a stable quiescent current. Note there are lots of SMT components under the board.

Diamond buffer

The Diamond buffer is an interesting, if poorly named circuit, which I first came across in an *Elektor* oscillator design (February 1979). It is a class-AB push-pull mirror-image circuit that has curvature cancellation, giving very low distortion of 0.0018% at $1V_{rms}$ into 600Ω with no overall feedback. The transistor input bias currents also cancel out, assuming good H_{fe} matching. Despite its name I can't see a 'diamond shape' in it; rather it has a 'crossover' like the classic multi-vibrator. I don't know what the 'diamond' refers to, its name seems to derive from Burr Brown blingy marketing. The circuit in Fig.45 needs six transistors, which is rather a lot for a buffer. The *Elektor* version was simplified down to four transistors by using bootstrapping for the input transistors' collector loads. Note the thermal linking of the transistors to reduce drift. A practical application is for the buffers in active filters, such as the active speaker crossover shown in Fig.46.

PCB

A PCB for the discrete buffer is available from the PE PCB Service – layout, Fig.47.

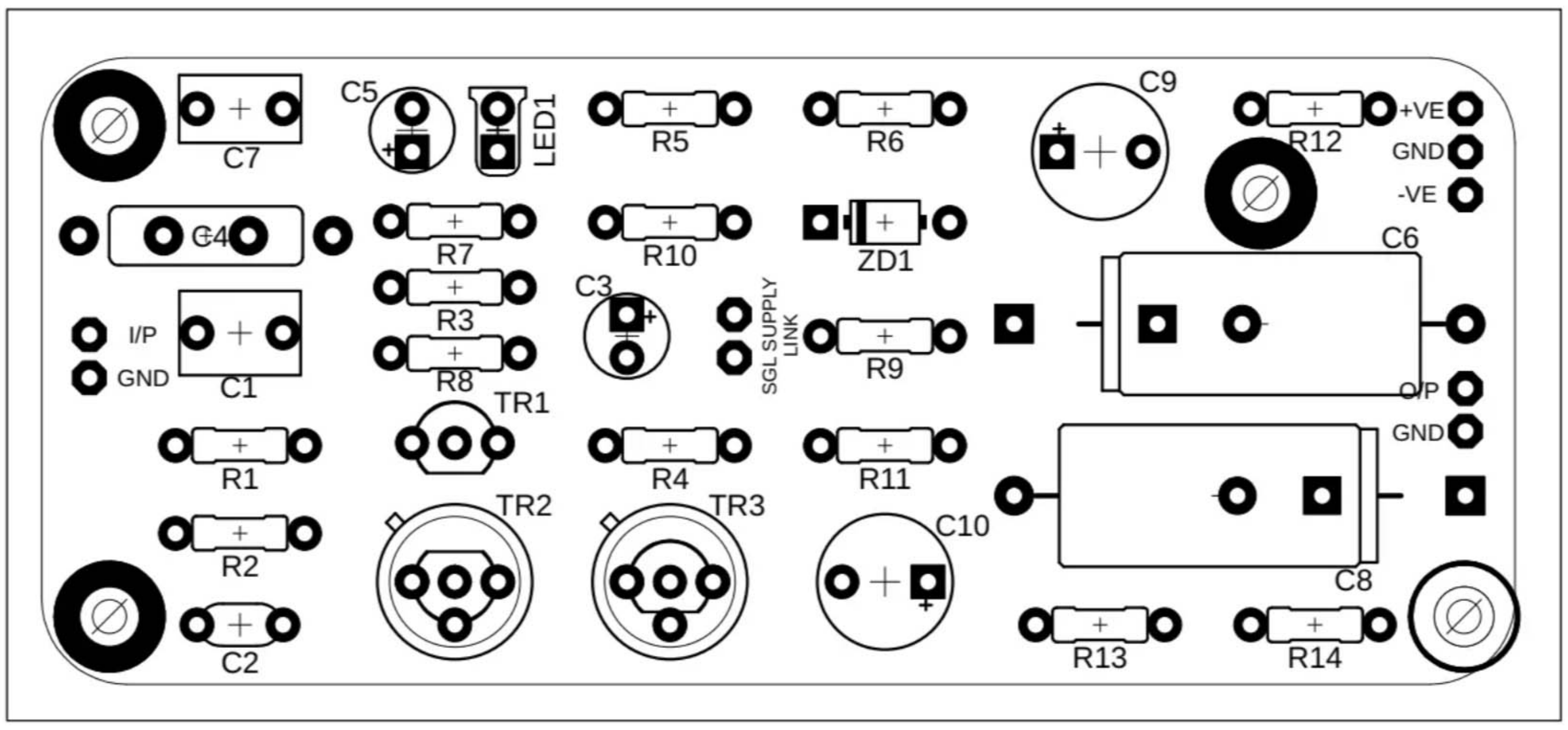
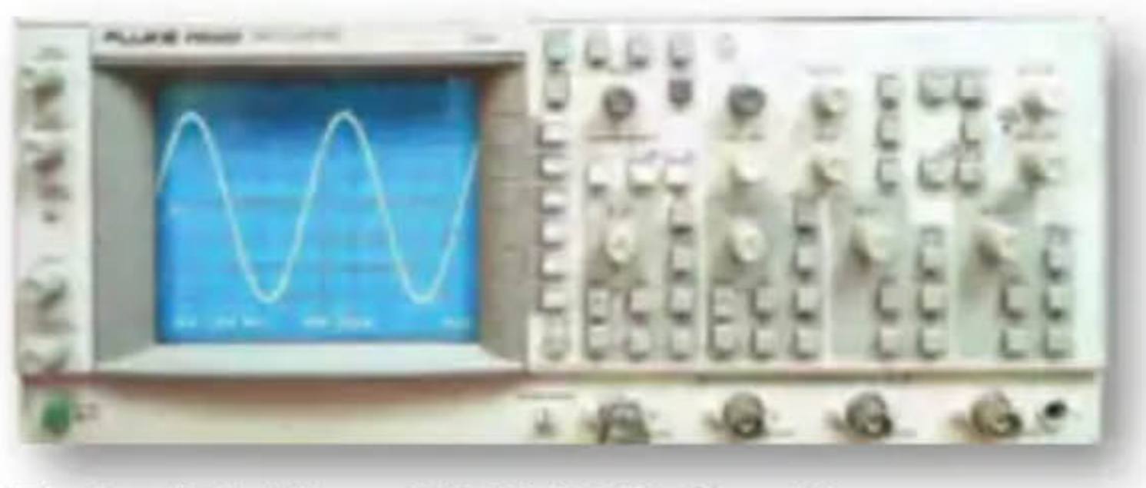


Fig.47 Held over from last month, the overlay diagram for the PCB for last month's three-transistor discrete buffer circuit.

Software sorrow… and a little serendipity

During the test phase for the discrete buffer I thought I had a fault with my AP audio analyser – the output drive level seemed to be fixed at $1V_{rms}$, but I was wrong. Buried in the manual (six A4 ring binders), I found – after a year of use – that the analyser was running a fixed test routine (macro) each time I clicked on the little THD icon. If I went to the sweep menu and clicked 'start with append' I could then change the output drive level with at least three more entries and clicks. I was amazed to find the unit could actually deliver $26V_{rms}$ ($36.9V_{pk\text{-}pk}$) at 0.0002% THD into a 600Ω load. This is very useful for performing component stress tests. I was even able to produce distortion in resistors! But that's for another column. I'm sure there are many other settings I could use better, does anyone out there know how to use an AP SYS-2712 to its full potential?



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IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
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HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
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HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
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HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
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HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
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Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
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Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
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Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

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Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
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Datron 1081	Autocal Standards Multimeter	POA
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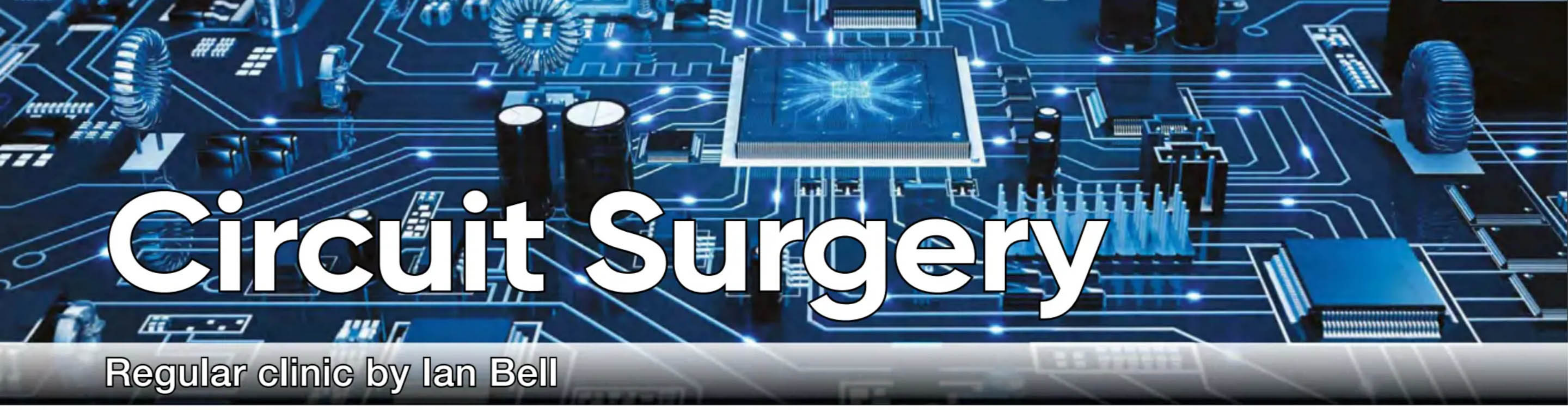
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio
Communications Test Set – £800



Circuit Surgery

Regular clinic by Ian Bell

Topics in digital signal processing – sampling

This month, we will start to look at various topics related to digital signal processing (DSP). DSP covers a wide range of electronics applications where real-world signals such as sound, images, temperature, pressure, position and speed are converted to digital data for manipulation, analysis, storage and display. The resulting processed digital information, or new information which has been generated digitally, can also be converted into real-world signals for human consumption (eg, audio and video) or manipulation of the physical world (eg, mechanical and thermal). These systems can be relatively complex (for example, streaming movies from the internet or control of industrial robots) or relatively simple (for example, a basic microcontroller measuring temperature).

Fig.1 shows the key elements of DSP systems, with a signal path from analogue input via digital processing to analogue output. The input signal passes through an analogue antialiasing filter which removes frequencies that would otherwise cause errors. A sample-and-hold circuit captures the filtered input signal at the points in time at which it is to be digitised. The process of sampling, and the use of antialiasing filters are key concepts in DSP and will be discussed in more detail in this article. An analogue-to-digital converter (ADC) produces digital codes that represents the values of the analogue signal at the input sampling instants. The digital processing performs operations on the digitised signal (data); this can be implemented directing in digital hardware or by software running on a processor.

The result of the digital processing of the input signal (or results of direct digital generation) are converted to analogue values at the output sample times using a digital-to-analogue converter (DAC). The output of the DAC is a 'stepped' waveform which is converted to a smooth analogue waveform by the reconstruction filter. Fig.1 shows key components in a generic DSP system, but not all DSP systems will contain all these components. For example, digital generation does not require the input half from Fig.1 and the system's output may not require a DAC if it is just one or more on/off controls, or a pulse-width-modulated signal.

Sampling and quantisation

We assume that analogue signals can have an infinite number of possible values between their upper and lower limits (peak values). We also assume that their value may be different (by some arbitrary small amount) after an infinitely small change in time. This is not strictly true when you consider that electric current depends on discrete charge carries (eg, electrons) and quantum effects come in to play when at sufficiently small scales. However, for the majority of analogue electronic circuit designs it is reasonable to assume this property for analogue signals.

On the other hand, digitised analogue signals can only have a finite number of possible values. This is because they are represented by digital code values, which have a finite number of bits. An ADC/DAC with an *N*-bit output/input digital word can handle at most 2^N different values. When an analogue signal is digitised, the process of going from an effectively infinite number of possible values to a finite one is called quantisation and is an inherent property of ADCs. We will look at ADCs (and DACs) in more detail in a later article.

Digitised (sampled) analogue signals also only change to a new value after a finite amount of time – this is the fundamental nature of sampling, where the signal value is captured and stored for processing at specific points in time. Sampling usually occurs with a fixed time interval (called the sample period, *T*) between sample points. A sampling period of *T* corresponds with a sampling frequency (or rate) of $1/T$. Sampling frequency is a key performance parameter of DSP systems. In the most basic approaches, the sampling frequency is the same throughout the system, but it is also possible to use different rates in different parts of a system. For example, initially sampling the analogue signal at a relatively high rate, but effectively resampling (within the digital part) to a lower rate for performing the processing operations (this is called 'downsampling' or 'decimation').

A signal defined at a set of sample times is referred to as a discrete time signal, to distinguish it from a continuous time signal. Digital (DSP) circuits process discrete time signals, but it is also possible to build analogue circuits which work with sampled signals. These use continuous-value analogue signals that update to new values at each sample point. Switched-capacitor circuits are an important example of this technology, and are widely used in integrated circuit design.

Sampled signals

The top plot in Fig.2 shows a set of sample points, with sample period *T*, on an analogue waveform. The sampled signal itself, in its most general form, is just a set of values associated with the sample times. It does not have a value between these times – this is illustrated in the middle waveform in Fig.2. This representation fits directly with digital data – a set of discrete values stored in a digital circuit, computer memory or other media.

If sampled values are processed in an analogue circuit, then the signal is often held constant between sample points and waveforms typically have a stepped appearance, like the bottom plot in Fig.2. This is the waveform that would be seen at the output of both the sample-and-hold and

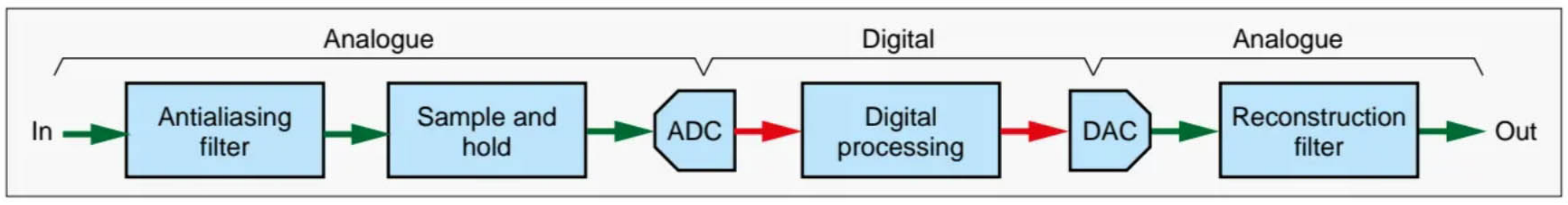


Fig.1. Generic DSP system structure.

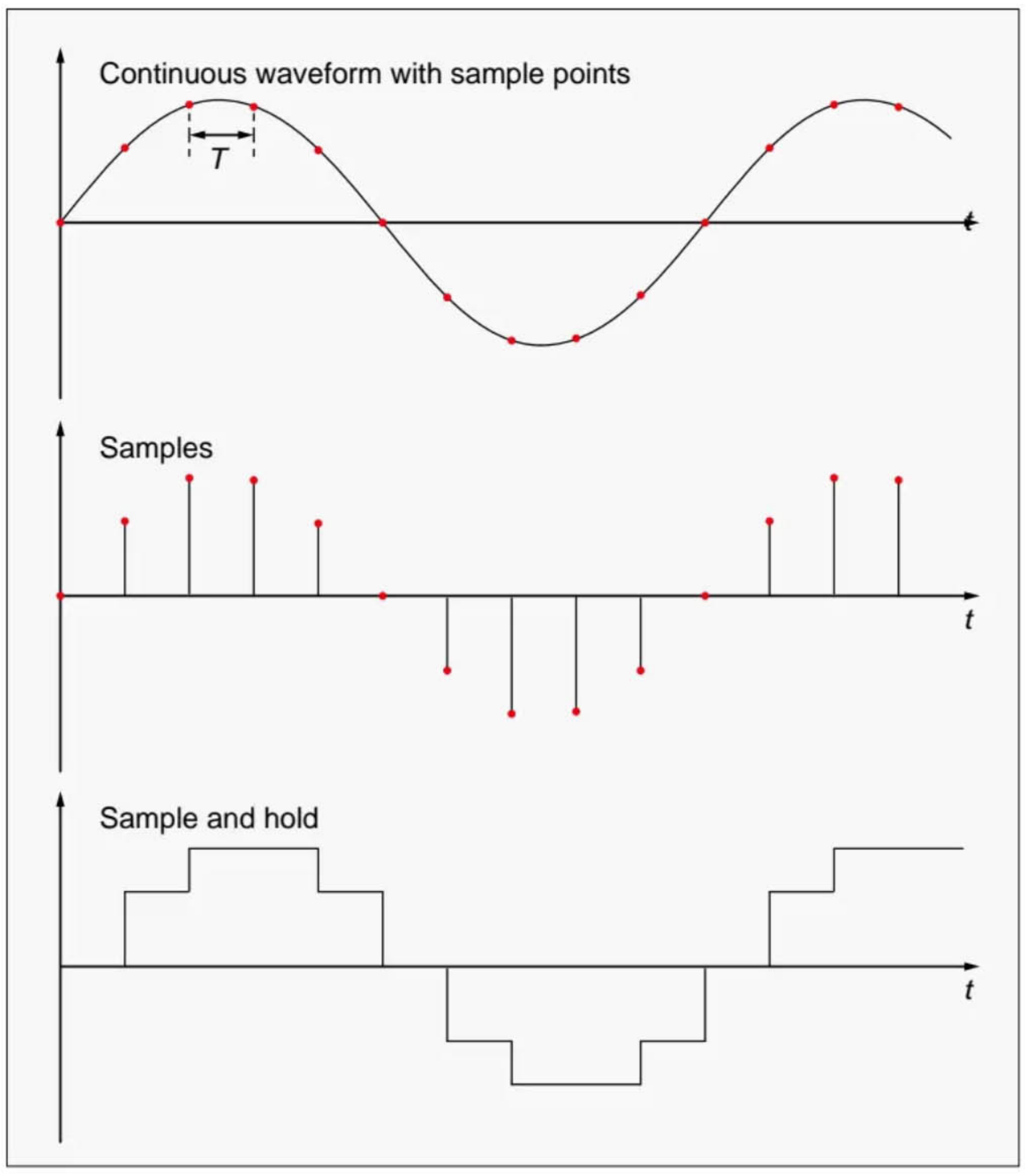


Fig.2. Sampled waveforms.

DAC blocks of the generic DSP system shown in Fig.1. The input waveform is sampled at each sample time and held at this value until the next sample time. At the ADC input the flat parts of the waveform provide the ADC with a constant input during the time it takes to perform the conversion. If the value being converted is not exactly equal to the signal at the sample time then errors will be introduced into the digitised signal.

The stepped waveform (particularly at the DAC output) is a called a zero-order hold. It represents the creation, or reconstruction, of a continuous-in-time analogue signal from a discrete set of samples. This is an interpolation process – we need to fill in the gaps between the sample points to create a waveform that is continuous-in-time. This is similar to finding the 'line of best fit' for data points on a graph.

The term 'zero order' refers to the mathematical principle of approximating a function (or set of data points) with a polynomial. A polynomial function of x is of the form $a_0+a_1x+a_2x^2+a_3x^3$… and so on, where the a_n terms are numerical values. The order of the polynomial is the highest power of x used. A zero-order polynomial just has a constant value – a flat line that does not change with x (or t for time in the case of the waveform). It is possible to create higher-order 'holds'; for example, a first-order hold produces a straight-line value change between sample times. However, these are relatively rare/advanced techniques in DSP systems.

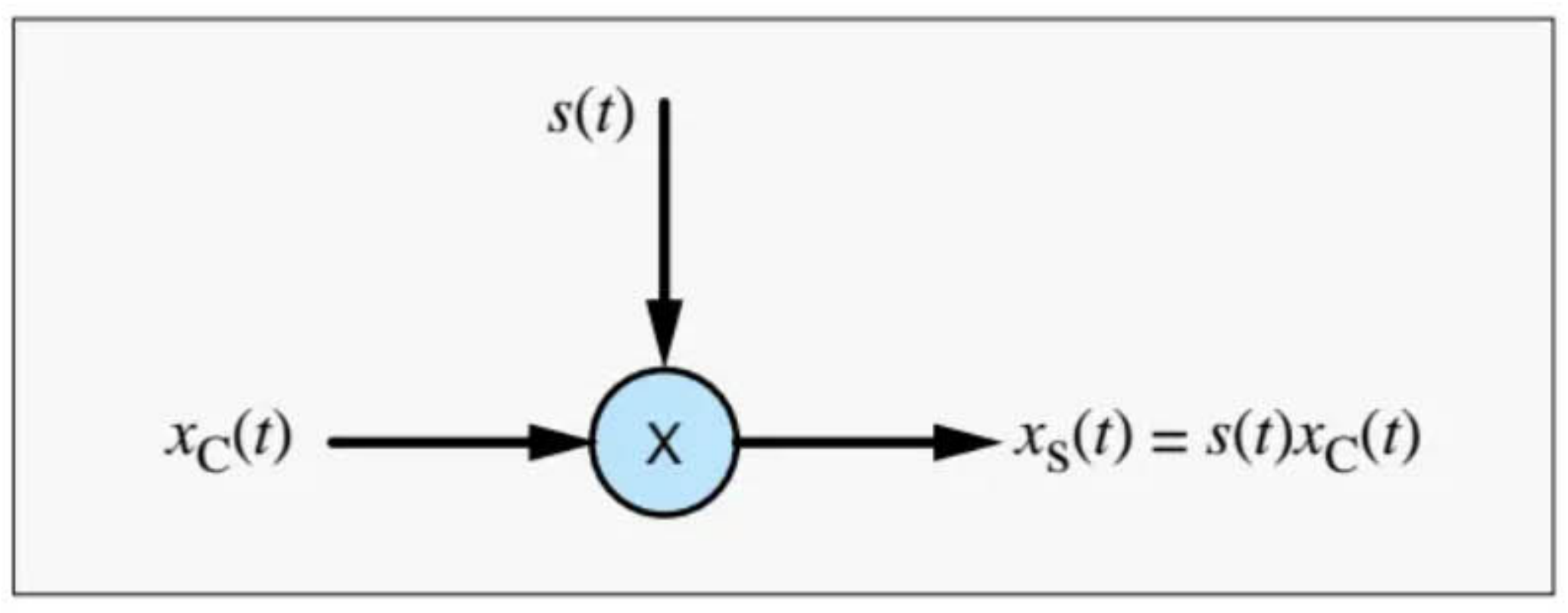


Fig.3. Simple model of sampling a signal with a pulse train.

If we sample an analogue signal, convert it to digital with an ADC and then convert it directly back to an analogue signal with a DAC, the resulting zero-hold signal is not an accurate reconstruction of the original signal, However, assuming the sampling was performed correctly, the original signal can be reconstructed by passing the DAC output through a low-pass filter – the reconstruction filter shown in Fig.1.

Aliasing

The first block in Fig.1 is called the 'antialiasing filter', so an obvious question is, what is aliasing and why do we need a filter for it? Aliasing is a problem which can potentially occur in any signal processing system which samples the signal. This includes all digital audio and video signal processing. Digital imaging sensors such as cameras and scanners can also suffer from aliasing effects. Aliasing is so called because it causes ambiguities in the sampled data, that is, there could be more than one signal which resulted in the same set of sample values – thus one signal is an *alias* of the other. Aliasing effects can be observed in everyday life; one often-quoted example is the 'wagon wheel effect' where the wheels of a vehicle in a film or video (perhaps a stagecoach in a western, as the name suggests) appear to be turning at the wrong speed, backwards or even stationary. Search online for 'wagon wheel effect' videos if you would like to see some examples.

A video camera samples the scene in front of it at a certain number of frames per second. If the wheel of a vehicle in the shot rotates an exact number of whole revolutions in the time between frames it will appear to be in the same position in each frame. When the film is viewed the wheel will appear to be stationary despite the fact that the vehicle is obviously in motion. However, if the wheel was rotating much more slowly, or if the video frame rate was much higher, we would get a large number of frames per revolution and playback would look as it should. This leads us to the insight that problems will occur if the input (the scene in this case) contains frequencies relatively close to the sampling frequency.

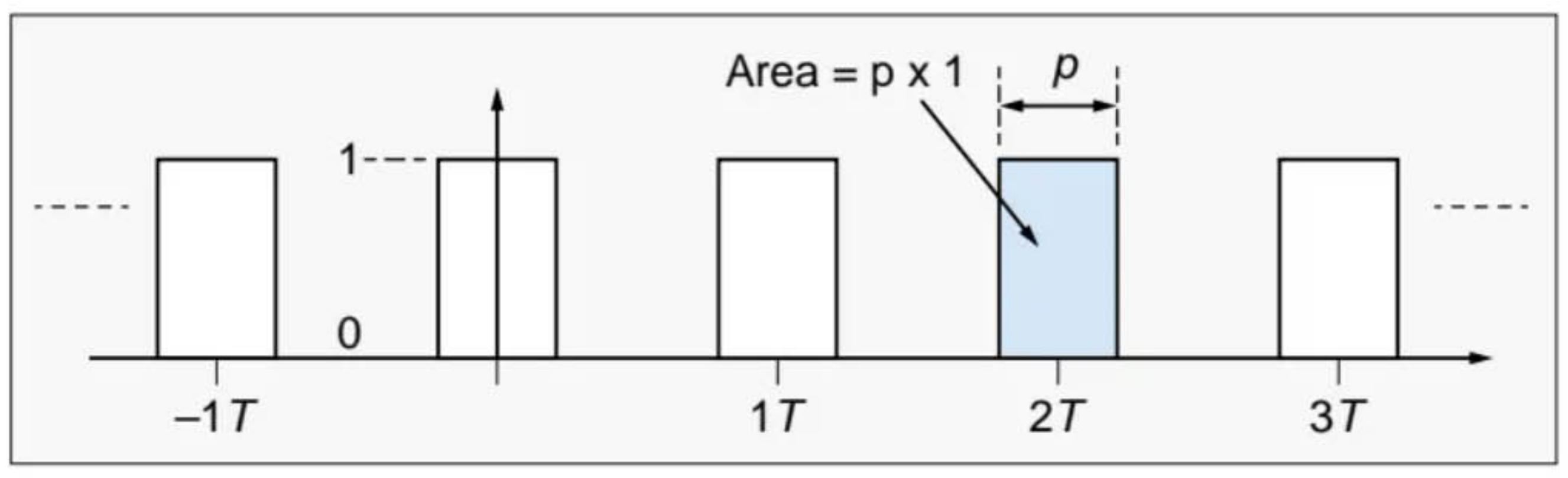


Fig.4. Sampling pulse train *s*(*t*).

Moiré aliasing patterns occur when a digital camera has trouble imaging an intricate pattern, the result is visual artefacts in photos or videos. A well-known example is a finely striped or patterned shirt (eg, on a TV presenter) causing strange waves or swirl patterns to appear in a digital image. This happens when the pixel size is similar to the pattern size and is less common than it used to be due to the increase in resolution of digial cameras and video presentation.

Any sampling process can be affected by potential ambiguities. This includes manually making real-world measurements (eg, of temperature). Imagine measuring the temperature in a garden once a day in the afternoon and plotting the results. The shape of the graph is likely to be an inaccurate representation of the temperature changes. For example, there is likely to be a daily cycle with lower temperatures at night. An actual near-constant temperature and strong day-night cycle with similar temperature each afternoon will produce the same form of graph with this measurement schedule. Measuring every hour would give a much more accurate picture of what was happening. The choice of sample rate requires an understanding of the signal being sampled.

Sampling concepts and nomenclature

An idealised sampled signal ($x_s(t)$), which only exists at the sample points, can be approximated by multiplying the continuous signal ($x_c(t)$) by a train of short-duration, unit-amplitude pulses ($s(t)$). This is a conceptual model rather than practical implementation and is illustrated in Fig.3. The pulse train signal is shown in Fig.4. The duration of each pulse (p) is ideally zero.

There is a potential problem here in that a unit amplitude pulse of duration zero simply disappears. As p reduces to zero the area under the pulse on the graph ($p \times 1$ – see shading on Fig.4) becomes zero. Fortunately, there is a mathematical solution – a function called the unit impulse or Dirac delta (written as $\delta(t)$) which is defined to be zero everywhere *except* at time zero, but does 'exist' in the sense that the area under the Dirac

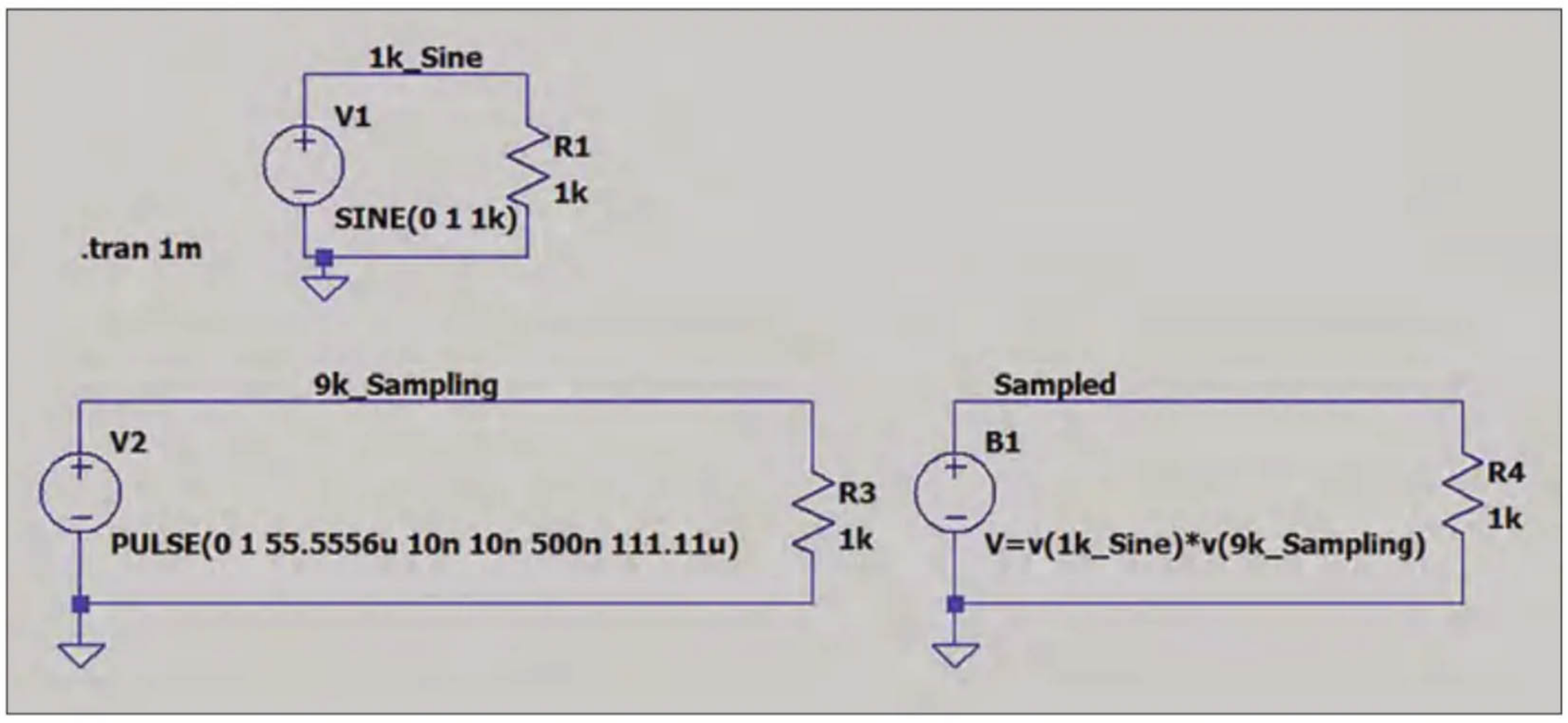

1k_Sine
V1
R1
1k
SINE(0 1 1k)
.tran 1m
9k_Sampling
V2
PULSE(0 1 55.5556u 10n 10n 500n 111.11u)
R3
1k
Sampled
B1
V=v(1k_Sine)*v(9k_Sampling)
R4
1k

Fig.5. LTspice schematic to create a sampled waveform.

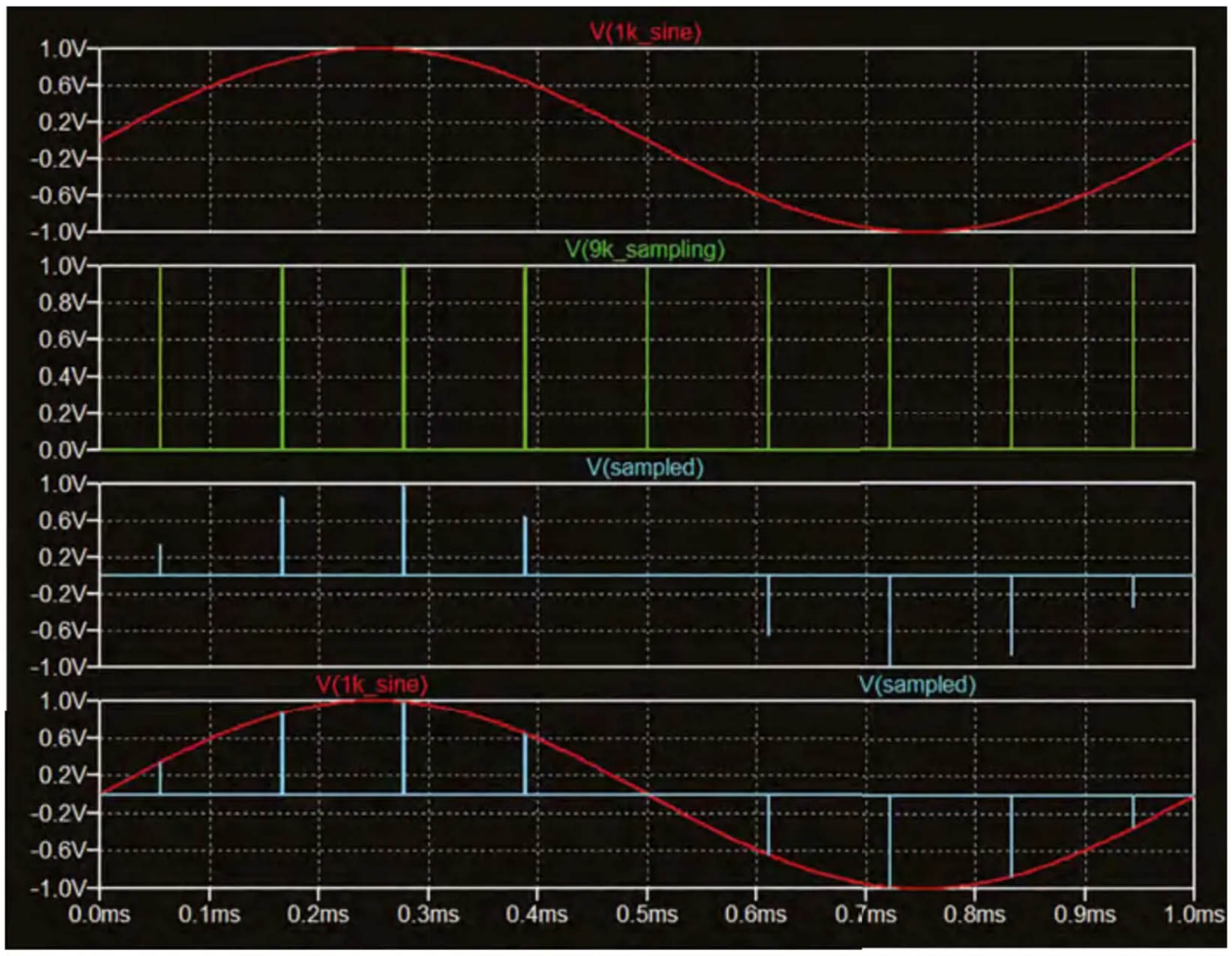


Fig.6. Results from simulating the LTspice schematic in Fig.5.

delta pulse is not zero, despite its zero duration. The area under the Dirac delta is by definition, a value of one. This is a useful mathematical abstraction which occurs frequently in the mathematics of sampled signal processing and is widely used in other areas of physics and engineering. It is worth being aware of the impulse concept even if you do not want to get into all the advanced maths that it gets used in.

The sampling pulses occur at multiples of sampling period T; that is, there is a pulse at time $t = 0$, $t = T$, $t = 2T$, $t = 3T$ and so on. There can also be pulses before the nominal reference time zero ($t = 0$), at times $t = -T$, $t = -2T$ and so on. In general, mathematical analysis of signals often assumes they are of infinite duration.

The term $x(t)$ means the value of the signal x as a function of time (t), which is what we generally refer to as a waveform. The symbol t is taken to refer to continuous time, and the original continuous signal ($x_c(t)$) has defined values for all values of t. However, for the sampled signal the value is only defined at integer (n) multiples of T, that is nT, so we can write $x_s(t)$ as $x(nT)$. With the 's' subscript being less necessary as nT implies sampling.

Since T represents the time difference between samples it is also sometime written as ΔT, the symbol Δ (upper-case delta) meaning a difference between values of a variable. In its most abstract form, a set of samples is just a sequence of values, and we can refer to these using an index for the position in the sequence, that is $x(n)$ rather than $x(nT)$. For example, we can describe calculations performed on sampled data, where each step occurs at the sampling interval, just using $x(n)$ and other relative samples in the sequence such as $x(n-1)$ and $x(n+1)$ to reference the values used in the calculation. If you look at websites and books on DSP you will often see terms such as $x(nT)$, $x(n\Delta T)$, $x(n)$ and $\delta(t)$ and variants of these in the equations used in these sources.

LTspice sampling pulses

We can create sampled signals based on the model illustrated in Fig.3 and Fig.4 using LTspice. This can help us illustrate sampling concepts such as aliasing. The LTspice model in Fig.5 creates a 1kHz sinewave using source `V1`. A 9kHz sampling pulse train is created using source `V2`. The sinewave and sampling pulses are multiplied by behavioural source `B1` to produce the samples signal in the manner shown in Fig.3. The pulse width of the sampling pulses is chosen to be small but easily visible on the plots because our main aim here is to create illustrative graphs.

The result of the simulation is shown in Fig.6. The top trace (red) is the 1kHz sinewave. The second trace (green) shows the sampling pulse train and the third (cyan) the sampled waveform. The bottom trace has the original sinewave and sampled waveform shown together to confirm that the sample pulses align with the original waveform.

Fig.7 shows a couple more sinewave signals added to the schematic in Fig.5;

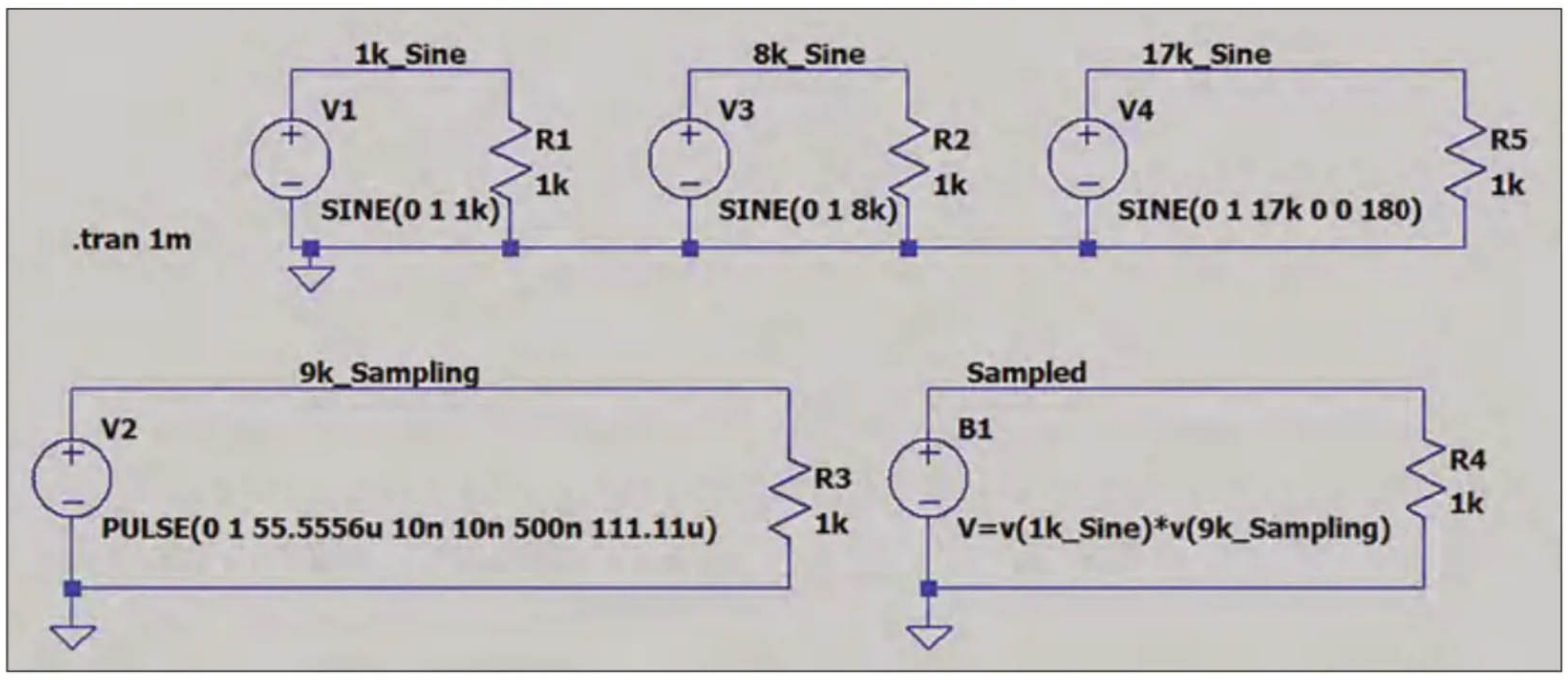


Fig.7. Adding more sinewaves to the schematic in Fig.5.

Introduction to LTspice

Want to learn the basics of LTspice? Ian Bell wrote an excellent series of *Circuit Surgery* articles to get you up and running, see *PE* October 2018 to January 2019, and July/August 2020. All issues are available in print and PDF from the *PE* website: **https://bit.ly/pe-backissues**

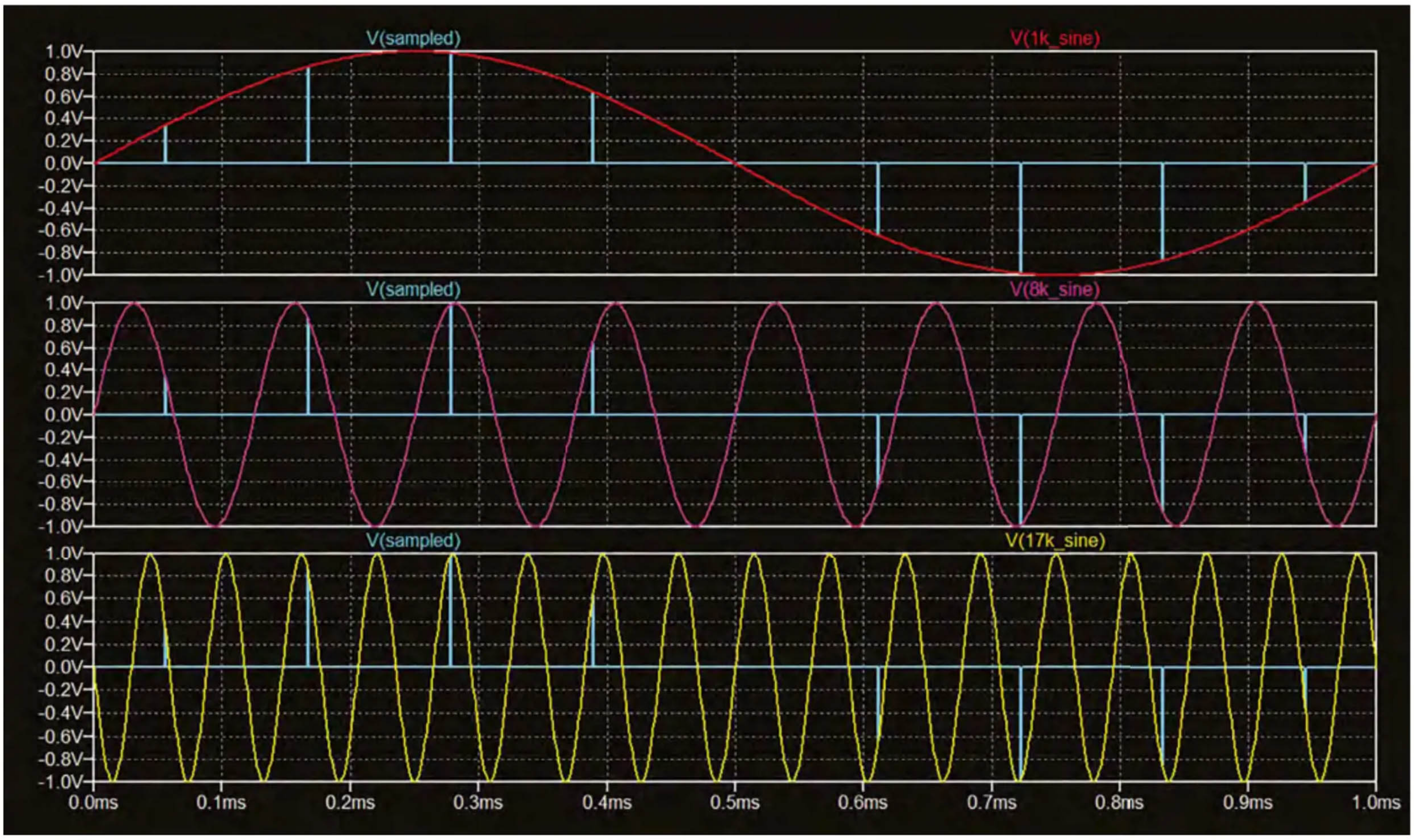


Fig.8. Results from simulating the LTspice schematic in Fig.7. All three waveforms will produce the same set of samples and are therefore indistinguishable after sampling.

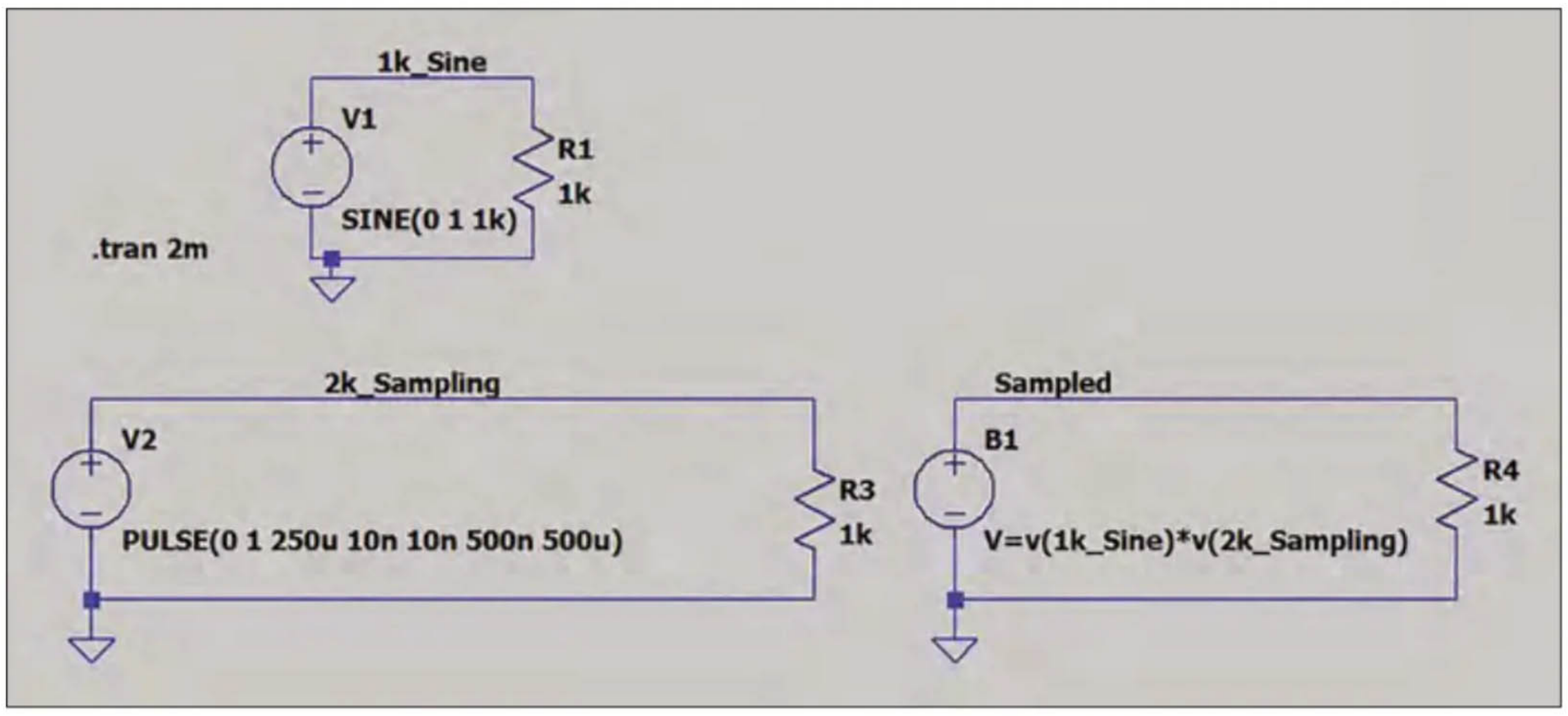


Fig.9. Sampling at exactly the Nyquist rate.

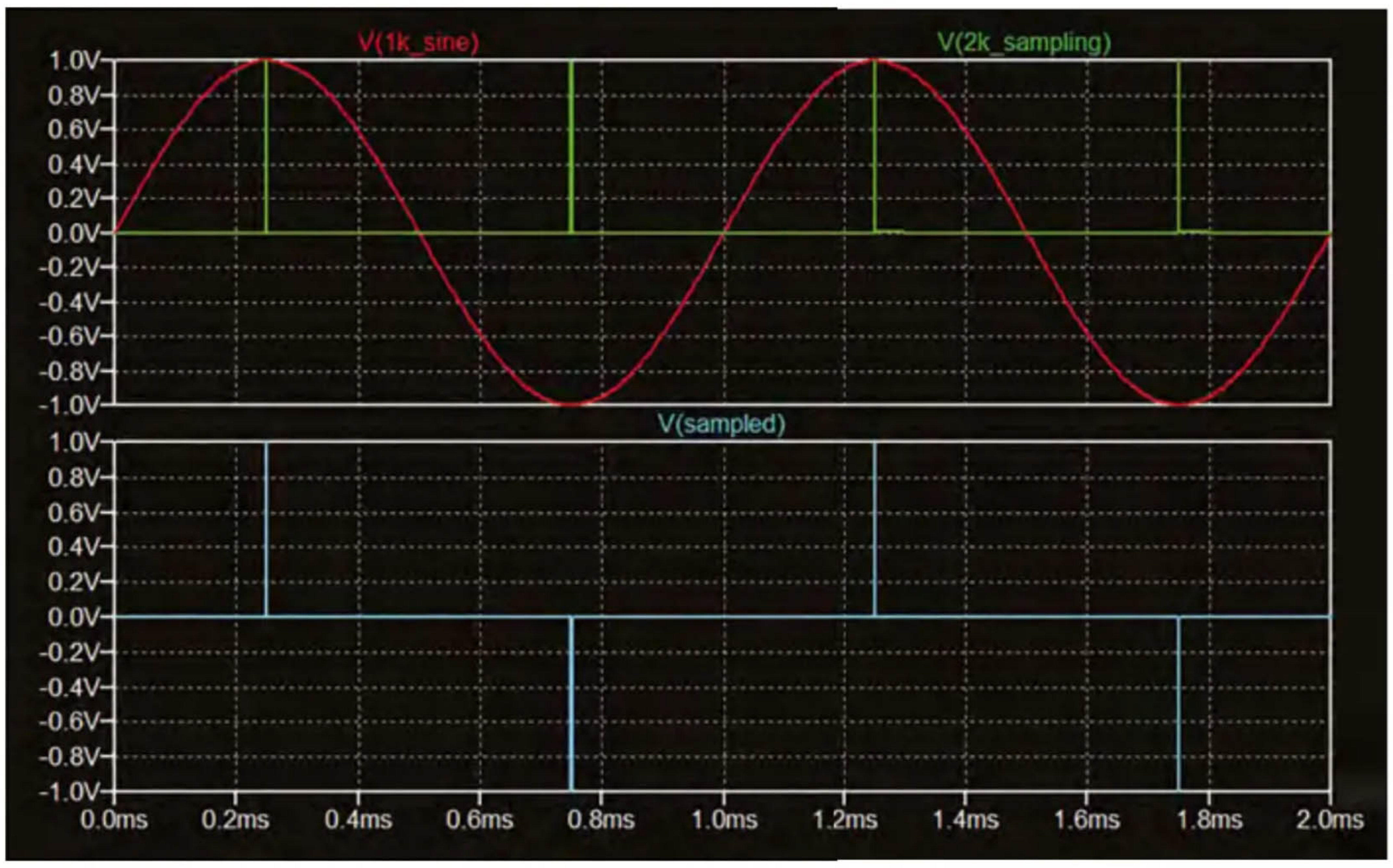


Fig.10. Waveforms of sampling at exactly the Nyquist rate, example 1.

these are 8kHz and 17kHz. The simulation results in Fig.8 show that the sample pulses from sampling the 1kHz sinewave at 9kHz exactly line up with the other two sinewaves. That means that if we sample a 1kHz, 8kHz or 17kHz sinewave at 9kHz we get the same set of samples. Thus, once we only have the sample data (further through the signal processing system, or in a digital storage), we cannot tell if the data was originally due to a 1kHz, 8kHz or 17kHz sinewave. In fact, there are many more sinewaves that will also produce the same sample data with 9kHz sampling.

Another way to look at this is that if we sampled an 8kHz sinewave at 9kHz then when the signal was reconstructed (eg, when playing a digital audio recording) we may end up with a 1kHz tone instead of the original 9kHz. The output contains something that was never there in the first place – just like the illusionary stationary or backward-turning wheels on the 'wagon'. Real audio signals, such as voice and music, are generally much more complex than single sinewaves, but the same aliasing processes can occur during sampling. The resulting output may contain tones which were not in the input, resulting in a loss of fidelity.

Nyquist rate

Mathematical analysis of the process of sampling a signal shows that signals with a frequency of less than half the sampling frequency are reliably represented in the sampled data. This is known as the

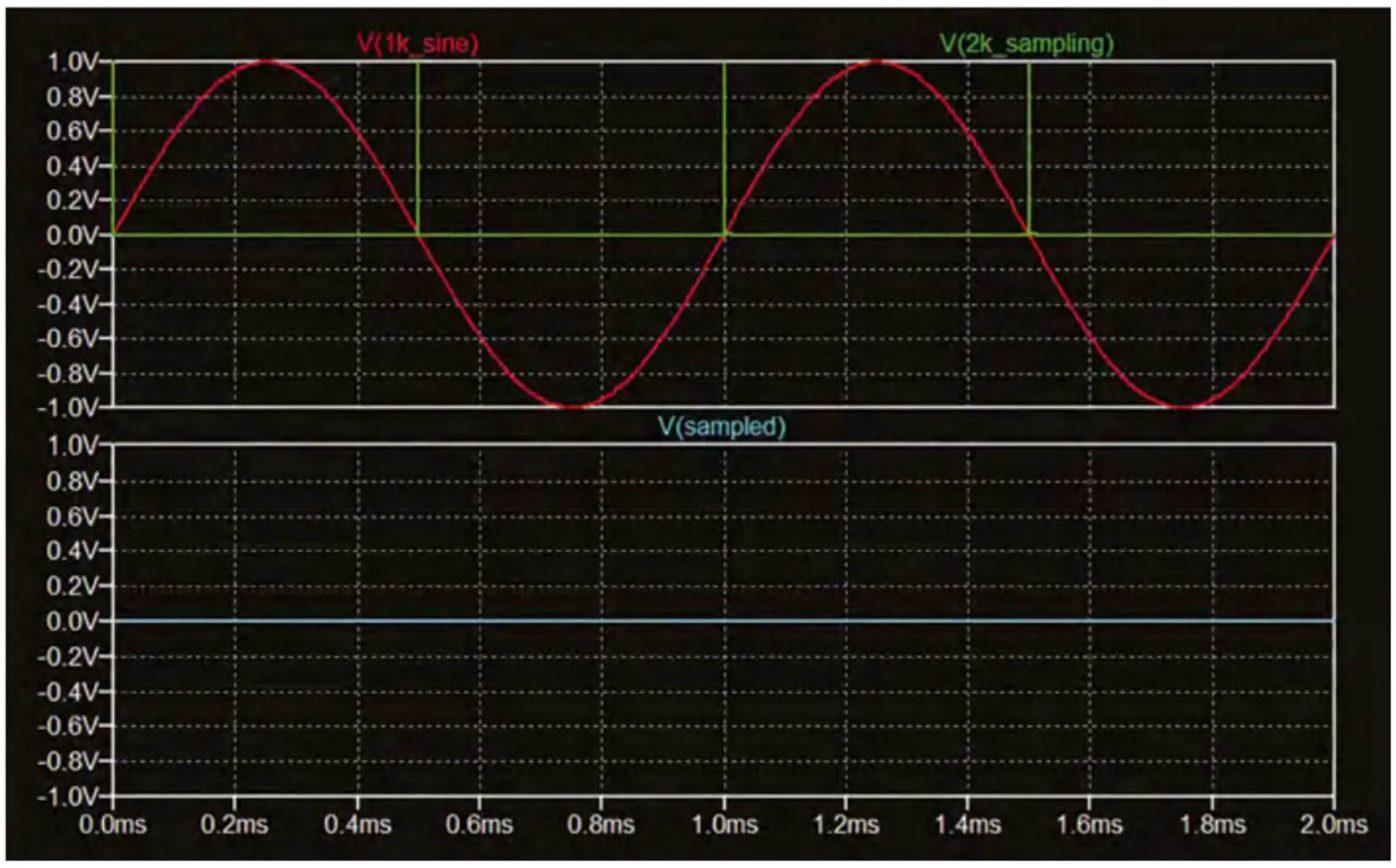


Fig.11. Waveforms of sampling at exactly the Nyquist rate, example 2.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*. The examples and files are available for download from the *PE* website: https://bit.ly/pe-downloads

Nyquist sampling theorem (also known as the sampling theorem, the Nyquist-Shannon theorem and the Whittaker-Nyquist-Shannon sampling theorem, the names honouring people who first published significant work on the topic). The theory shows that if the input does not contain any frequency components at or beyond half the sampling frequency then it is possible to perfectly reproduce the original signal from the sample data.

A sampling frequency of twice the maximum signal frequency is called the Nyquist frequency or Nyquist rate. Sampling at less than this frequency is called 'undersampling' (which does have its uses). Sampling at a rate significantly higher than the Nyquist rate is called oversampling and facilitates low-noise, low-distortion signal processing. Sampling at exactly the Nyquist rate may enable the signal to be recovered but the results may be wrong for specific alignment of the samples and waveform. This is show in the simulation in Fig.9 to Fig.11. The schematic (Fig.9) is similar to Fig.5 but with 2kHz sampling rather than 9kHz (that is exactly twice the 1kHz signal frequency).

Example results are shown in Fig.10 where it can be seen that the samples exactly align with the peaks in the sinewave. These samples will produce a square wave at 1kHz when passed to a DAC, which will in turn produce a 1kHz sinewave when passed through a suitable reconstruction filter – the sampled signal is successfully recovered. However, Fig.11 shows the same situation except that the sample pulses are shifted in time (the `Tdelay` parameter for the pulse source `V2` is changed to `0` instead of `250µs`). The sampling aligns with the zero crossing of the sinewave, so all the samples are zero and therefore the sampled signal cannot be recovered.

Antialiasing filters

If we remove all frequencies at and above half the sampling frequency from the input before sampling it, then we will not have any problems with aliasing. This is the job of the antialiasing filter. By sampling at just over the Nyquist rate it is theoretically possible to perfectly recover the sampled signal, but doing so implies a close-to-ideal antialiasing filter – we will discuss this in more detail in another article. In cases where there is certainty that the sampled signal does not contain frequencies at and above half the sampling frequency an antialiasing filter is not required.

Antialiasing filters are not only required in audio and video signal processing; the image sensors in digital cameras are spatially sampling the image projected by the lens onto the sensor. If the image contains small repetitive details aliasing can occur. To overcome this, an optical filter is used to provide an amount of blurring which will prevent aliasing. However, in recent years more digital cameras have become available without anti-aliasing filters. These provide better image quality in situations where aliasing would not occur.

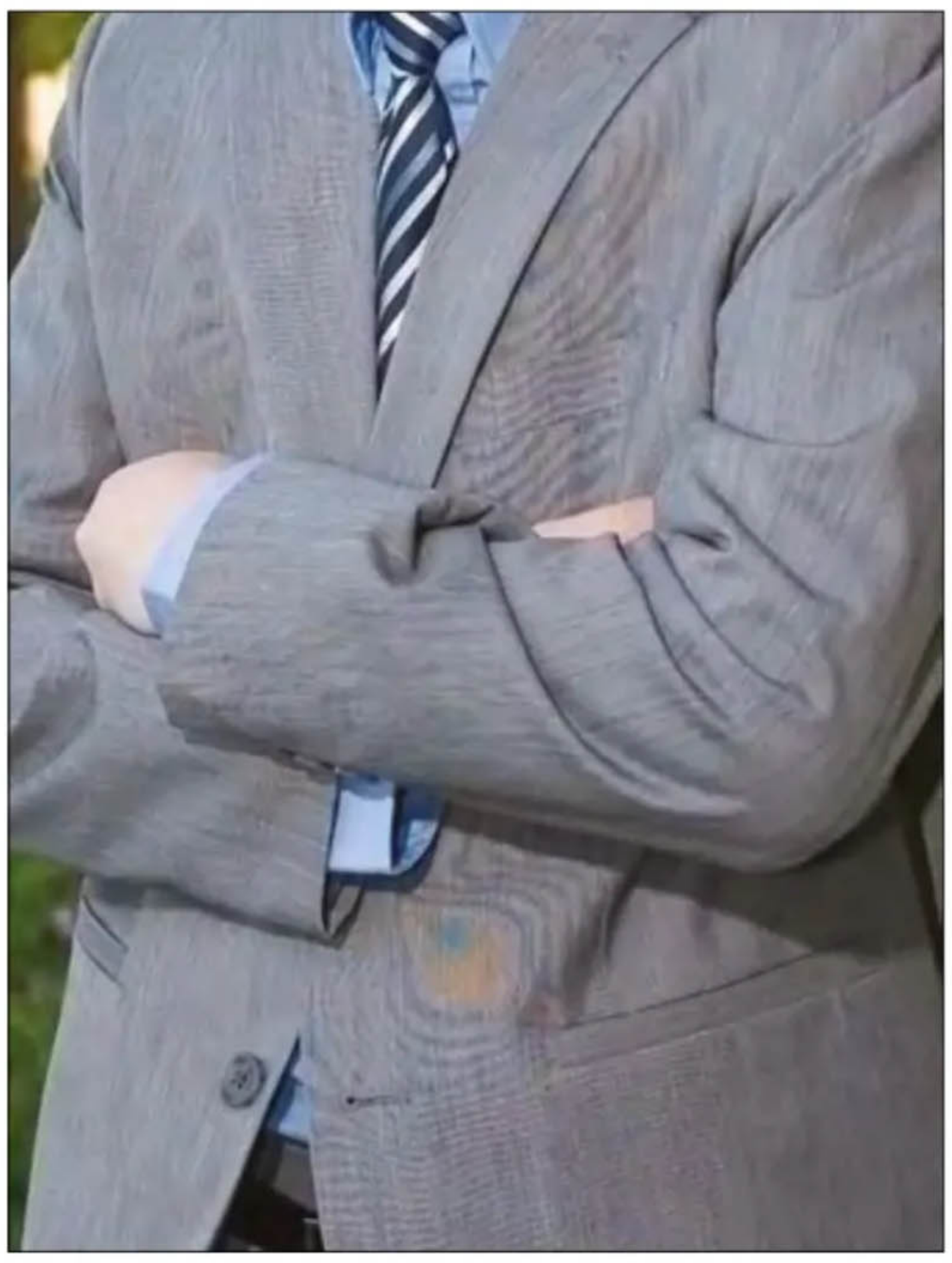


Fig.12. The moiré effect in photography is an example of aliasing. It creates artifical stripey patterns when images are captured with repeating patterns that match the spatial frequency of the camera's sensor pixels.

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

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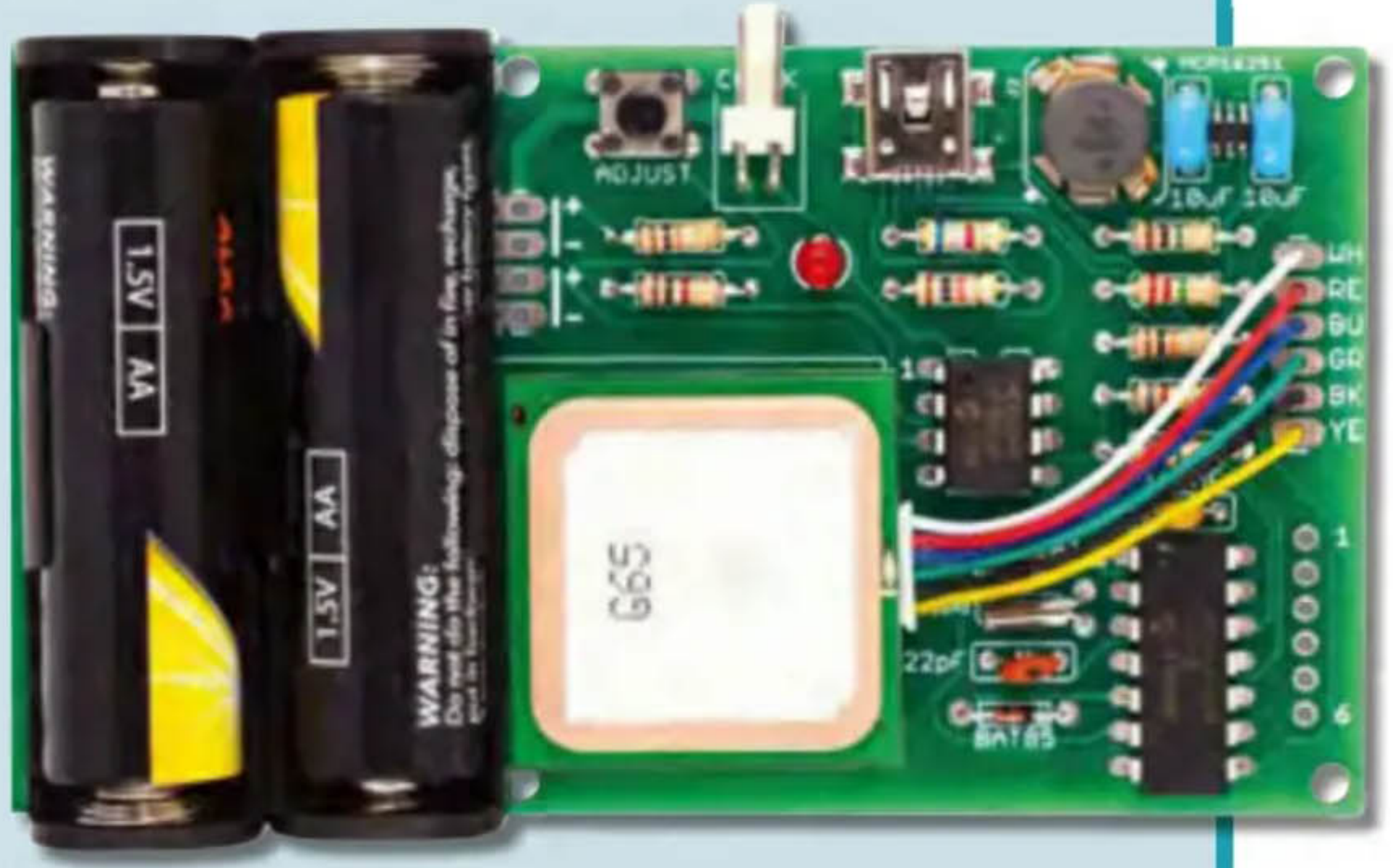
Next Month – in the June issue

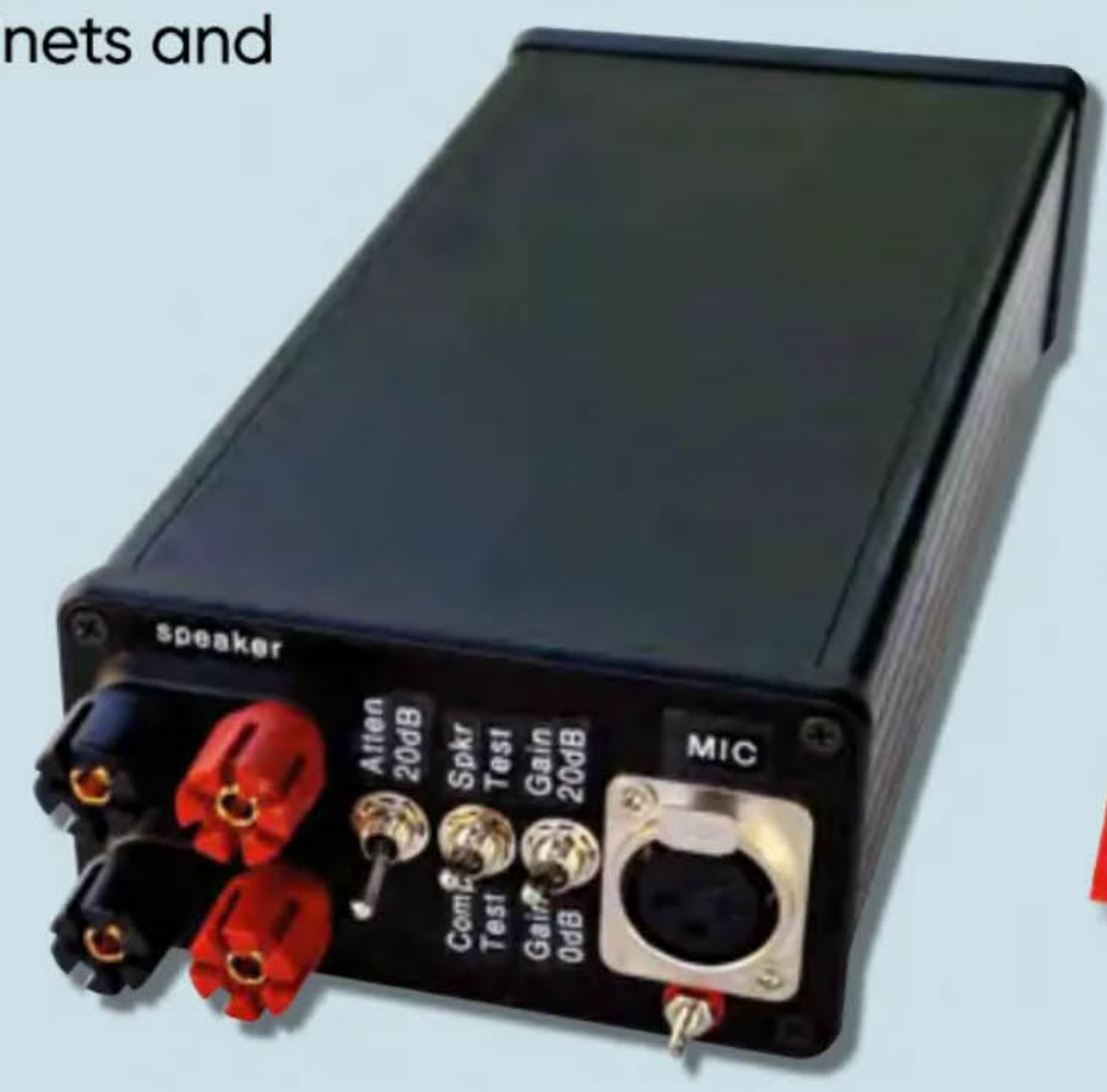


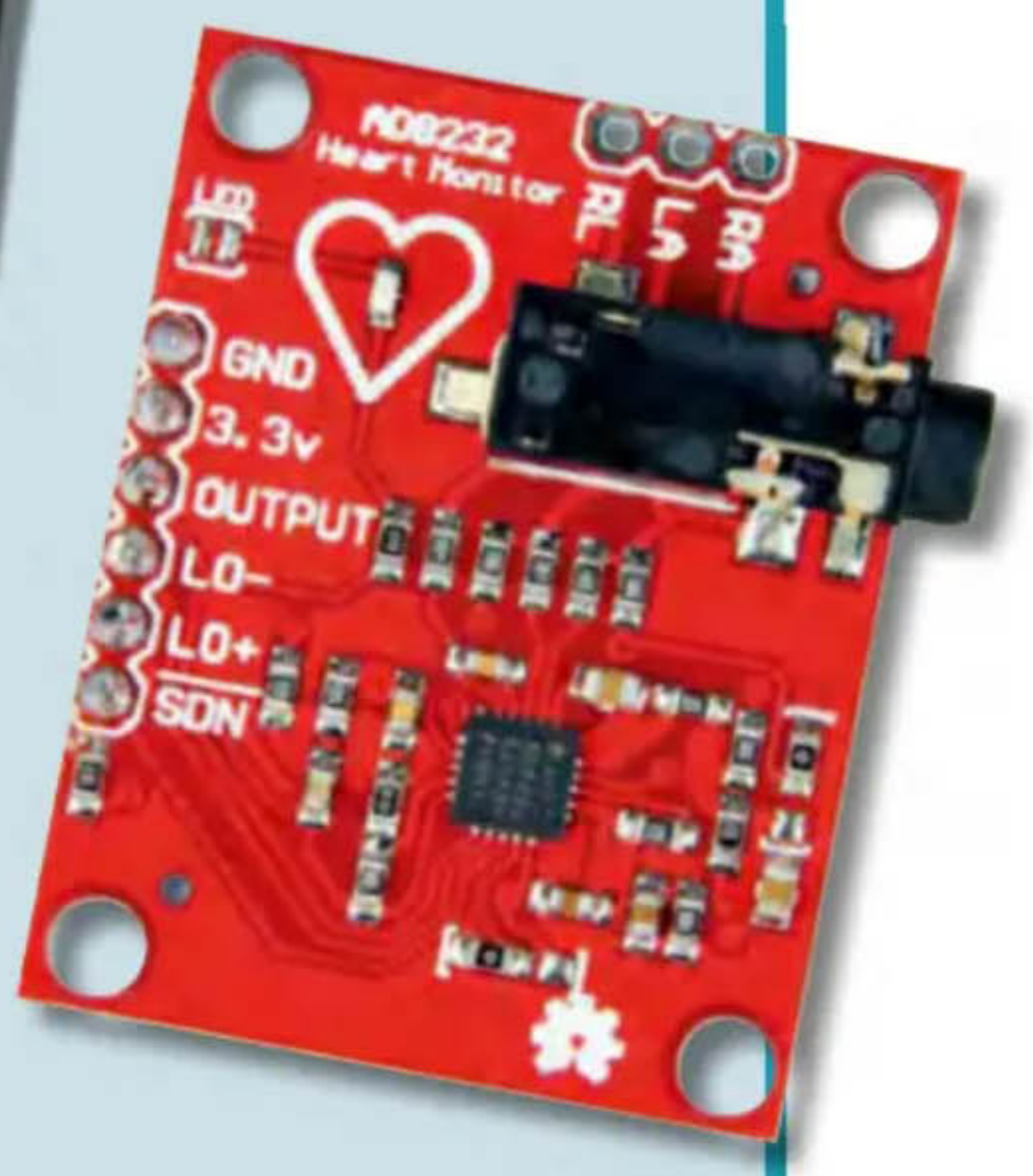
Wi-Fi Time Source for GPS Clocks

The Raspberry Pi Pico W can be used as a substitute for GPS modules in existing time keeping designs, for when you can't get a reliable GPS signal. It gets the time from an internet NTP server via Wi-Fi and is accurate to a fraction of a second.

Loudspeaker Test Jig

Use your computer's sound card to measure loudspeaker performance, inductors, capacitors and complex impedances. With this Jig and appropriate software, measuring and tweaking crossovers, cabinets and speakers is easy.





Heart Rate Sensor Module

The XC3784 kit features an Analog Devices AD8232 heart rate monitor front-end IC which forms the 'heart' of this module. It provides a low-cost way to monitor the operation of the heart via an Arduino MCU or similar. It comes complete with a matching three-electrode lead; a pack of additional electrode pads is also available.

PLUS!

All your favourite regular columns from *Cool Beans* and *Circuit Surgery*, to *MitchElectronics*, *Teach-In*, *Techno Talk* and *Net Work*.

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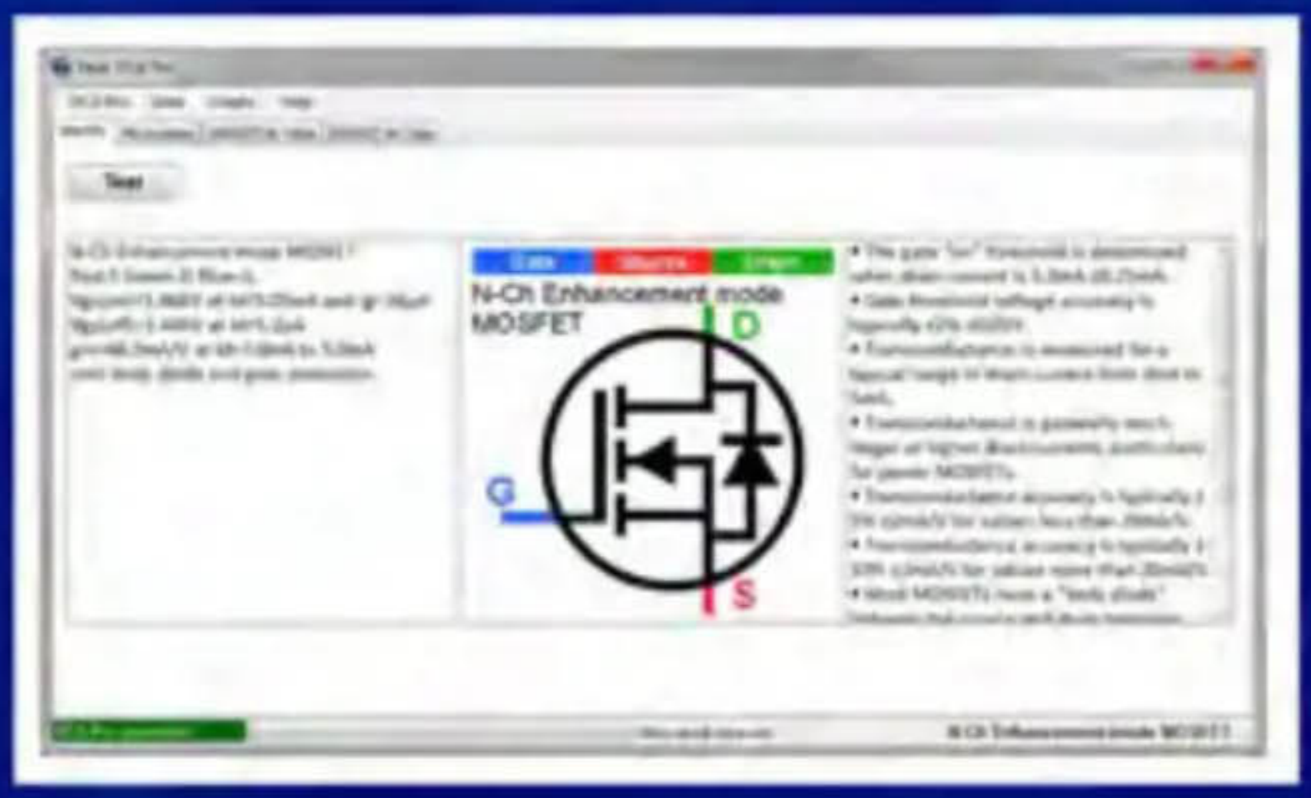
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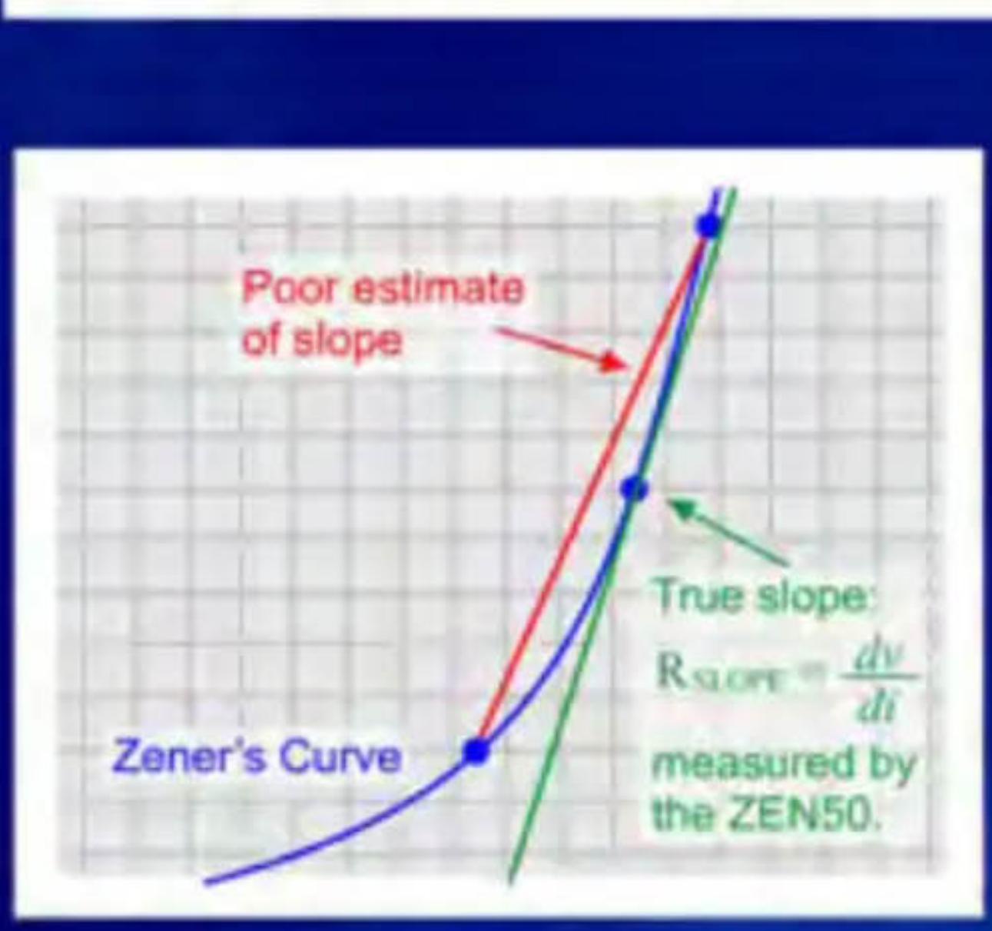

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